Towards a strategy for adapting to climate change in Alberta

by R.K.W. Wong, M. English, F.D. Barlow, L. Cheng and K.R. Tremaine

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Executive summary

There is a growing consensus among scientists that the earth's temperature is warming due to an increase in the "greenhouse effect" caused by carbon dioxide (CO_2) and other gases. This concern arises from results of simulation of the earth's climate using global climate models or general circulation models (GCMs) that estimate an increase in global temperature from 2 to 4°C within 40 to 60 years, should current trends in the emission of greenhouse gases continue. The models also suggest that regional climate changes could be much larger. The potential impact of a global climate change, coupled with recent drought conditions and weather anomalies in Alberta, has raised concern over this issue within the Alberta government. The desire to respond to this issue in an optimal fashion led to the initiation of this project.

The purpose of this study is to provide a preliminary assessment of these global effects on Alberta's climate. This purpose was addressed in the terms of reference of this six-month project by the following three tasks:

1. Assessment of the results of GCMs and what they say about the present and future climate of Alberta.
2. Analysis of the climate records of Alberta to determine if there is any evidence that the climate of Alberta is changing.
3. Identification of the strategic planning requirements of the participating agencies for adapting to possible climate change in Alberta.

The principal conclusions that can be drawn from the results of this study are given below:

1. The GCMs are the best available tools for future climate simulations. However, for purposes of regional scale application and assessment, there are large uncertainties associated with the model results. The GCM results do not reproduce Alberta's normal climate well. There are greater discrepancies in the precipitation estimates than in the temperature estimates. GCM simulations of climate under a doubling of atmospheric carbon dioxide suggest an increase of 3 to 7°C in annual temperature and a 7 to 30% increase in precipitation for Alberta. Such increases in annual temperature and precipitation would give Alberta a climate like that of present day Colorado. This situation is expected to be reached by the years 2030 to 2050. It must be noted that an increase in temperature will result in a change in the water balance at the earth's surface (because of increased evapotranspiration) irrespective of any change in precipitation.
2. In the 1980s (1981-1987), the average annual temperature of Alberta was warmer than normal (defined by the period 1951 to 1980) by about 0.2 to 1.4°C, depending upon location. Based on data from 1951 to 1987, the warming rate was estimated to have an average of 1.3°C per century and a maximum of approximately 4°C per century. With warming doubling in the winter season, a maximum increase of approximately 8°C in the average winter temperature over a century can be extrapolated from the present results. No significant change in precipitation was detected. Alberta's climate has significant regional differences. Overall there is a 5°C difference in mean annual temperature over the province and a difference of over 300 mm in annual precipitation, the minimum being in southeastern Alberta. The mountain areas to the west, exert strong local influences on the climate of Alberta. In fact, such local differences are reflected in the number of regions into which the province is divided by various users of climate information. Climate data from northern Alberta is sparse.

   Even without a change in climate variability, the shift in the mean climate is sufficient to change the frequency of extreme events. However, in analyzing climate records, the mean monthly range in temperature was the only indicator of climate variability and extreme weather events that was examined. In the 1980s a decrease in the mean monthly temperature range, from 0.8 to more than 2.0°C was detected, suggesting a decrease in the occurrence of temperature extremes.
3. The important conclusions from the user needs survey regarding the effects of climate change is that there is a lack of confidence in the climate model results. This lack of confidence is partly due to difficulties associated with the interpretation of climate information. Weather monitoring is carried out by a number of agencies but the data are not archived collectively and are therefore not easily accessible to others. Trained support staff are required to provide professional and consistent analysis and interpretation of climate data. Managers are willing to use climate variability and climate change information in the planning process if the information available is in an understandable form and associated uncertainties are identified. The survey also pointed out that water-related issues are major concerns of most users.

Introduction

Climate and climate change

Climate is commonly perceived as being average weather conditions. In fact, it is the result of complicated interactions between the atmosphere, the hydrosphere (basically the oceans), the land surface, the cryosphere (the icecaps), and in particular, the various activities of man. A more complete definition relates climate to the statistics from the state of the atmosphere-ocean-land system (Monin 1986). Because the concept of climate involves some sort of an averaging process, the question is then: From what length of time should the average be taken? There is no definitive answer to such a question. In practice, one usually thinks in terms of several decades (Monin 1986).

Because of the dynamic nature of our climatic system, the climate we encounter for any time period is likely to change from time to time. In order to consider change, one must first consider the reference point from which change occurs, i.e. change from what? Most commonly, the reference point is taken to be the 30-year normal computed from historical data, though even these 30-year normals vary as time proceeds. Climate change is therefore a relative concept. The important point is that the amount of change should be small enough and the rate of change slow enough so that our ecosystem can comfortably evolve.

Change in climate is more than just a change in the average state. A more complete consideration of climate should also involve information on the variability of weather within the period over which climate is defined. There are obvious reasons for this. First, the average is only one statistic for describing the population of weather conditions that constitute climate. An additional statistic for characterizing the variability of weather is needed to provide a more complete picture. A change in weather variability is also a climate change. Second, weather variability has more damaging effects on the ecosystem. This is manifested in the frequency of unusual or extreme weather events.

The greenhouse effect

The greenhouse effect is a natural phenomenon. It plays a central role in determining the earth's climate. It occurs when sunlight passes through the atmosphere and warms the earth's surface. The earth then radiates infrared energy, some of which escapes back into space. But certain naturally occurring, radiatively active gases (known as greenhouse gases) absorb most of the infrared radiation and emit some of this energy back toward the earth, warming the surface. To a large extent, this effect is responsible for making the earth conducive to life.

Concerns about the greenhouse effect have arisen out of apprehensions that anthropogenic (man-made) emissions of greenhouse gases will further warm the earth. Greenhouse gases – primarily carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and tropospheric ozone (O_3) – can be produced as by-products of human activities. Table 1 shows the concentrations and sources of these gases as well as their relative efficiency in absorbing infrared radiation. When these gases are released into the atmosphere and their concentrations increase, the greenhouse effect is compounded, resulting in an increase in mean global temperature.

There is a consensus among the scientific community that increases in greenhouse gas emissions will affect climate. Considerable uncertainty, however, exists with regard to the magnitude of the effect, its timing, and its regional pattern. In addition, there is a great uncertainty about changes in climate variability and regional impacts.

Once emitted, greenhouse gases remain in the atmosphere for decades or even centuries. In many

Table 1. Concentrations and sources of principal greenhouse gases (adapted from Bolin et al, 1986).

Principal greenhouse gas	**Concentrations (parts per billion)**			**Relative efficiency compared to CO_2**	**Man-made sources**
	present	**Trend (%/yr)**	**Projected 2030 AD**		
Carbon dioxide (CO_2)	345×10^3	0.4	450×10^3	1	Burning of coal, oil and gas; deforestation
Methane (CH_4)	1.55×10^3	1.1	2.34×10^3	25	Biological activities related to increased human and bovine global population
Nitrous oxide (N_2O)	301	0.3	375	250	Increased use of fertilizers; burning of coal, oil and gas
Chlorofluorocarbins					
F11	0.17	5.7	1.1	17500	Industry
F12	0.28	6.0	1.8	20000	
Tropospheric ozone (O_3)	Variable	-1	+12.5%		Photochemical reaction of other gases

cases, drastic reductions in emission rates would be required to stabilize atmospheric concentrations. Trace gases released over the last century (Figure 1 shows the concentrations of CO_2 at Mauna Loa since 1958. Legge (1988) also reported an observed CO_2 concentration of 345.4 ppm in Alberta.) may have already committed the earth to a 2°C warming, greater than any other in the period of human history.

Recent work by Dickinson (1986) suggests that the effects of a greenhouse gas buildup, radiatively equivalent to doubling the preindustrial concentration of CO_2, might warm the planet by 1.5 to 5.5°C; the best guess involves equilibrium warming of between 2.5 and 4.5°C. These temperatures are comparable to the increase that has occurred since the last ice age; however, the period of time within which this increase could now happen is much shorter. If no policies for limiting greenhouse gas emissions are effected, the equivalent of a doubling of CO_2 is expected to occur between the years 2030 and 2050. It is uncertain whether our ecosystems and economic systems will be able to adjust to such a rapid change in mean global temperature. Increases in the world population, coupled with limited environmental and agricultural resources, lead to an increase in the vulnerability of social systems to climate change.

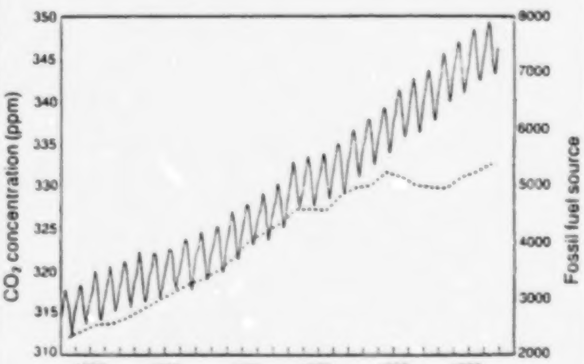


Figure 1. Carbon dioxide concentrations and fossil fuel CO_2 emissions at Mauna Loa. The solid line depicts monthly concentrations of atmospheric CO_2 at Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. The steadily increasing concentration of atmospheric CO_2 at Mauna Loa since the 1950s is caused primarily by the CO_2 inputs from fossil fuel combustion (dashed line). Note that CO_2 concentrations have continued to increase since 1979, despite relatively constant emissions; this is because emissions have remained substantially larger than net remove, which is primarily by ocean uptake. (Sources: Keeling 1983, Komhyr et al. 1985; NOAA 1987; Conway et al. 1988; Rotty 1987).

Global climate change

A global warming of approximately 2 to 4°C would result in a world different from that which exists today. Global climate change will have significant impacts on natural ecosystems; when, where, and how we farm; the availability of water; how we live in our cities; the wetlands in which our fish spawn; recreational beaches; and all levels of government and industry.

Detailed regional predictions of climate change cannot be made at this time. Thus, potential responses to greenhouse gas buildup must be viewed in the context of risk management or buying insurance. Allowing decision makers (public and private) access to easily interpretable information will enable them to make optimal responses to the anticipated climate change; such information is best considered as a public good to be supplied by government agencies.

Global warming is an international problem, the solution to which will require extensive cooperation between both industrialized and developing countries. Clearly, no single country nor economic sector can deal with the issue independently. Stabilizing strategies will require global cooperation of an unprecedented nature and may be costly to some countries.

In order to respond effectively to this problem, the nations of the world must act in concert. Several international organizations have recognized this need and have become involved with the global climate change issue. The United Nations Environment Programme (UNEP) is responsible for conducting climate impact assessments. The World Meteorological Organization (WMO) is supporting research on the atmospheric and physical sciences. The International Council of Scientific Unions (ICSU) is developing an international geosphere-biosphere program. The Intergovernmental Panel on Climate Change (IPCC), established under the auspices of UNEP and WMO, will attempt to ensure an orderly international effort in responding to the threat of global climate change. In addition, several countries have held, or plan to hold, international conferences on global climate change.

Climate change in Canada

In recognition of the impact of climate and climatic fluctuations on society, Canada established a Canadian Climate Program (CCP) in 1978, under the leadership of the Atmospheric Environment Service (AES) of Environment Canada, to integrate the efforts of various federal and provincial agencies as well as the universities and the private sector in the field of climatology. One of the program's components has, since 1984, focussed on research aimed at assessing and identifying the potential social and economic impacts of climate warming if atmospheric carbon dioxide doubles.

The Canadian Climate Centre has been increasingly involved in international climate change issues and since the Changing Atmosphere Conference took place in Toronto in 1988, has been active in intergovernmental climate change activities. Another high priority activity of the Canadian Climate Centre is the upgrading of computing facilities to meet an increased demand for climate data and the incorporation of non-AES data into the climate archives.

Provincial government departments have also been active in the climate field. The Province of Quebec Environment Ministry has operated a climate service centre for a number of years. There is much interest in Newfoundland in locating such a centre at Memorial University.

In 1984, an interdisciplinary project was initiated to study the potential impacts of climate warming on Ontario (Cohen and Allsopp 1988). This involved the anticipated results of a doubling of carbon dioxide. The project team included participants from the federal and provincial governments, the universities, and the private sector. Studies included the impacts on water resources, agriculture, forestry, energy, tourism and recreation, and in particular, the socioeconomic impact on Ontario. The project was coordinated and supported by the Canadian Climate Program, which is also involved in other similar provincial efforts to study the impacts of climate change.

Climate change in Alberta

Global temperature change estimates are only indicators of the rate and magnitude of climate change. Climate change at the regional level, caused by global warming, will vary in both magnitude and timing, and changes in precipitation and other factors will be as important as changes in temperature. It is to be expected that changes in the hydrological cycle and in ecosystem functions will carry the main social impacts. These will be regional changes because both involve intimate interaction with the earth's surface. Particularly for Alberta, with its nonuniform topography, regional differences will be important.

The AES has commissioned a number of studies relevant to the impact of climate change in Alberta. A study on the implication of climate change for agriculture in the Prairie Provinces has been completed. Results from this study suggest that the impact of climate warming on crop yield, using the CO_2 doubling scenario, varies markedly with different climate change scenarios and different prairie regions. The latter variation is largely due to the precipitation changes that will probably accompany climatic warming; these range from substantial increases in precipitation in some regions to decreases in other regions for different time of the year.

Studies on the implications of climate change for forestry in the Prairie Provinces and Northwest Territories are currently underway. A report from a study concerned with the "environment/economy link in Alberta - implications under climate change" is expected shortly.

These studies all tend to focus on national regions the size of a province, rather than the smaller provincial regions of interest to decision-makers in Alberta.

Awareness of the dependence of Alberta's economy on climate and climatic fluctuations has existed in Alberta for many years, and Alberta has been a national leader with respect to the number of climate-related studies undertaken. For example, in 1956, the Alberta Research Council and the AES jointly initiated the hail studies project, which became a world leader in the development of weather modification technology. In 1972, Richmond Longley of the University of Alberta published "The Climate of the Prairie Provinces", a classic that is still widely used today. The Alberta Climate Advisory Committee is the most active of the provincial climate advisory committees and in 1987 organized a successful symposium/workshop on the impacts of climate variability and change on the Canadian Prairies. In addition, the Alberta Climatological Association provides for the exchange of scientific and technical information on climate activities in Alberta. In 1988, the Alberta government devoted an entire issue of "Environment Views" to the changing atmosphere. Just recently, Alberta Energy has taken the lead in Canada and has completed a study entitled "Energy-related CO_2 emissions in Alberta, 1988-2002" in preparation for possible incoming federal guidelines concerning limitations of CO_2 emissions because of concerns about climate change. Finally, the Alberta Environmental Centre in Vegreville is currently exploring methods of monitoring greenhouse gases, especially methane.

Climate change also offer the potential for substantial economic opportunities. The key element in successfully adapting to these changes will be our ability to mitigate the negative effects and to take advantage of the benefits. Although the specific rate and magnitude of future climate change in Alberta is difficult to predict, the rate of greenhouse gas buildup during the next century will depend heavily on future patterns of economic and technological development. These are, in turn, influenced by the policies of local, provincial, national, and international private and public institutions. In keeping with the theme of "anticipate and prevent", a number of Alberta government departments and the Research Council felt the need to move towards the development of a strategy for adapting to climate change so that Alberta could fully participate in the economic opportunities arising from it. A project concerned with assembling the information required for such strategic planning was initiated in December 1988.

Towards a strategy for adapting to climate change in Alberta

Central to the planning of the Alberta climate change project were the recommendations that came out of the Symposium/Workshop on the Impact of Climate Variability and Change on the Canadian Prairies, held in Edmonton in September 1987. To a large degree, the recommendations dealt with quantifying climate variability and change. There was a need for a more definitive knowledge of current climate variability and potential climate change. Once these were better defined, it would be possible to consider the biophysical impacts that could be expected from climate change. The biophysical impacts would lead to socioeconomic impacts.

The development of strategies for adapting to climate change requires information on the societal impacts of climate change, which are the real bases for policy development. Climate change information must be translated into information on societal impacts before any decision concerning strategy can be made. The various sectors of the economy will require different types of climatic information for strategy development. It is necessary to identify these needs and examine ways in which they can be met. It is, however, not intended as part of the present study to examine the general or any specific area of climatic impact. The word "towards" in the title of the project is emphasized.

Acquiring information concerning potential climate change is the necessary first step towards strategy development. There is, however, a distinct difference in the spatial scales involved. Climate is a global issue in the sense that it is the global climate system that determines Alberta's climate. Societal impacts and strategy development, however, are Alberta's own regional concerns. In the flow of information towards strategy development there must somehow be a scale transformation so that the scale of climate information is consistent with that for strategy development. In this study, a preliminary look at this scale transformation involves examining the usefulness of global climate models in supplying climate information for regional impact assessments.

In the face of the distinct possibility of global climate change, policy makers worldwide are concerned with the development of strategies for adaptation to, or even prevention of, human-induced climate change. In Alberta, a significant portion of the economy, and the quality of the natural environment for both humans and wildlife, are closely related to weather and climate. It is therefore important to examine Alberta's requirements for climate information and assess the usefulness of sources such as climate models to provide such information. In addition, it is important to examine the climate data base of Alberta and determine whether the information could be used as a monitoring tool for climate or for detecting any indications of climate change. The present six-month project was a preliminary investigation. The problems are too large and complex, however, for solutions to be obtained within such a short time.

The purpose of the project was therefore threefold. First, climate modelling approaches were to be reviewed and the performance of GCMs for application to Alberta was to be assessed. Secondly, climate data for Alberta were to be analyzed for the purposes of revealing any signs of significant climate change. Finally, the needs and concerns of users of climatic information were to be identified.

Model assessment

Review of climate models

Models of the atmosphere-land-ocean climate system range in complexity from very simple to highly sophisticated. The simplest of all climate models involves a single parameter: the mean temperature of the earth. This can be determined by simply equating the mean daily uptake of solar radiation by the earth's surface to the outgoing radiative heat flux. Such models are called integral-parameter models or zero-dimensional models. Although relatively simplistic in nature, the zero-dimensional models are useful in theoretical investigations related to the internal or external factors affecting climate, when such factors are incorporated in the modelling scheme. A recent study by Andersson and Lundberg (1988) involves the use of a zero-dimensional model to examine the delayed albedo effect on the climate system.

At the next level of sophistication, one-dimensional climate models provide additional details in terms of the variations in a climate parameter in one specific direction. For example, the variation in temperature with height, as represented by the standard atmosphere, can be considered as a one-dimensional climate model. Climate models for vertical variations in temperature can also incorporate various radiative fluxes as a function of height, whereas the horizontal variations are averaged over the entire global domain. Such models, incorporating greenhouse gas or aerosol distributions, can be used to study climatic effects due to changes in trace gases or aerosol concentrations in the atmosphere (Manabe and Wetherald 1967; Rasool and Schneider 1971). Other processes such as vertical convection, surface albedo, moisture distributions, and cloud-radiation interactions can also be parameterized in one-dimensional models. Hansen et al. (1981) described the use of a vertical, one-dimensional, radiative-convective model with cloud, albedo, and ocean parameters to study the results of increased greenhouse effects.

Because insolation is the primary energy source of the climate system and a strong dependence of insolation on latitude, one-dimensional climate models are often designed to simulate the latitudinal structure of the climate system based on this dependence. A typical formulation of this type of one-dimensional climate model uses the mean annual heat budget of the latitudinal zones. This can be as simple as the balance between the incoming radiation, outgoing radiation, and the large-scale divergence of the mean annual meridional heat flux. Budyko (1968) and Sellers (1969) used such models with different parameterizations of the three major components of the heat budget equation. The dependence of insolation on latitude also implies a significant latitudinal structure of the atmospheric circulation. This can be simulated by the zonally symmetric dynamic models with prescribed distributions of thermal and momentum sources. The prototype of such models is described by Eliassen (1952). Subsequent development of these models, at various levels of sophistication, are outlined by Pike (1971), Saltzman and Vernekar (1971), and Kurihara (1970). More recent applications include that of Rossow et al. (1982), who used a one-dimensional climate model to study cloud albedo feedback, and that of Kasting et al. (1984), who used a one-dimensional model to study the effects of high carbon dioxide levels on the surface temperature. Many of the physical processes represented in one-dimensional models are also represented in the more sophisticated models. Often one-dimensional models can be used for developing schemes for more elaborate models and for providing first estimates of climatic effects due to external changes such as the addition of pollutants. Two-dimensional climate models can be constructed using any two of the latitudinal, longitudinal, and vertical directions. While the vertical and latitudinal components are essentially the same as those of one-dimensional models, the longitudinal component represents additional details in terms of orographic and thermal forcing. This permits the inclusion of such features as cyclogenesis and large-scale atmospheric waves. Like the other low-order climate models, two-dimensional models are useful in various theoretical investigations of climate. Watts and Hayder (1984), for instance, used a two-dimensional energy balance model incorporating the distribution of continents and ice sheets to successfully test the Milankovitch climate theory.

The most sophisticated models of the climate system are three-dimensional global climate models or general circulation models (GCMs). Such models contain a set of time-dependent equations for the dynamical and thermodynamical state of the atmosphere. GCMs are numerical models that simulate the day-to-day evolution of the large-scale weather system, including some form of representation of the interaction between the atmosphere and the ocean. The coupling of the atmospheric and oceanic circulation has been studied by many, (Manabe 1969; Bryan 1969; Manabe and Bryan 1969; Manabe et al. 1975, 1979, Washington et al. 1980, Wells 1979, Pollard 1982, Hansen et al. 1983) and is still an active area of research (Hansen et al. 1988, and Manabe and Stouffer 1988). The ocean is as effective as the atmosphere in mechanically transferring heat, and is an important component of the climate system. Modellers of atmospheric circulation must collaborate with oceanographers for better simulations of climate.

The processes of primary importance that are simulated in a GCM are the heat balance of the earth and the associated atmospheric circulation driven by the spatial nonhomogeneity in heat distribution. Usually the equations governing the major processes are solved numerically using a grid system covering the globe. The values of different variables are computed for the different grid points. The number of grid points used is therefore related to the resolution of a GCM. For economic reasons, a GCM usually has grid point spacing of several degrees of latitude or longitude. There are also a limited number of height levels for the representation of the vertical distribution of computed variables.

Processes smaller than those resolvable by the grid system (subgrid scale processes) must be parameterized. Basically, this means that since the subgrid scale processes cannot be dealt with explicitly, one must express their effects on the larger scale processes statistically, while in turn determining the subgrid scale processes using variables computed on the larger scale. The parameterizations required for GCMs are determined by the processes of primary climate importance. Following is a brief description of the major processes parameterized in GCMs.

Radiation and clouds

A comprehensive computation of radiative transfer is complex and the actual schemes used in GCMs are dependent on the radiative processes modelled and the approximations used. Schemes are typically model- specific. Since the models may differ in many other aspects, it is generally difficult to get a clear impression of the different features of radiative calculation; however, comparisons of two schemes in otherwise identical forecast models have been examined by Geleyn et al. (1982). The inputs for radiative calculations are usually temperature and moisture, and distributions of trace gases and aerosols. For example, the distribution of carbon dioxide (CO_2) must be included in simulations for increased greenhouse effects, and the distribution of dust particles must be incorporated into the model for a simulation of the influence of a volcanic eruption.

Clouds and surface albedo are also parameterized quantities in GCMs. The description of cloud cover is perhaps the most uncertain part of radiative parameterization. Earlier models used climatological descriptions for cloud cover, but it is desirable to actually calculate cloud distributions in terms of model variables. This latter approach means that the cloud feedback processes, which are important aspects in many studies of climatic heat balance, must be simulated. Examples of numerical experiments using GCMs to study cloud processes include those by Schneider et al. (1978), Hunt (1978), Herman et al. (1980), and Manabe and Wetherald (1980).

The planetary boundary layer (PBL)

The PBL is the layer (with thicknesses varying from 100 to 1000 m) of the atmosphere closest to the earth's surface. For short-term weather forecasting (1 to 2 days), the PBL will not likely have much influence on the large-scale air flow (Driedonks and Tennekes 1981). For large-scale climatological investigations, however, in which cyclone development surface fluxes of mass, momentum, and heat, or topographic influences are important, a detailed representation of the PBL is required.

The PBL parameterization of GCMs may be divided into two classes based on the vertical resolution of the model. If there is at the most only one height level within the boundary layer, the so-called 'bulk' parameterization schemes are used. This means that the PBL is represented as a whole, with no details of the internal structure. Alternatively, the PBL structure may be explicitly represented. Such representation can often be crude, but it allows for the computation of PBL variables at several levels within the lowest portion of the atmosphere. Both categories of PBL parameterization may involve varying degrees of sophistication. For example, turbulent fluxes may be represented by eddy diffusivities and the spatial gradients of a certain field, or by a "higher-order" closure scheme, using computed local turbulent kinetic energy. Closely related to the PBL are the surface conditions that must also be parameterized in GCMs. These include the distribution of land and water bodies, terrain features, and surface covers. Often, surface energy and water balance computations are used to obtain estimates of surface heat, moisture, and momentum fluxes, and other important climatic variables such as soil moisture and surface runoff.

Convective and nonconvective precipitation

The parameterization of moist convective processes is used to compute precipitation. The schemes vary greatly in complexity and in computational costs. Manabe et al. (1965) proposed a simple scheme in which convection occurs when a model layer is saturated and the lapse rate is greater than the moist adiabatic rate. The amount of precipitation is calculated using the amount of moisture that must be removed from the air to ensure that the relative humidity does not exceed 100% (or a lower specified threshold value). Kuo (1965, 1974) developed another system in which the occurrence of convection depends not only on instability, but also on the convergence of moisture in the large-scale flow and surface fluxes. A portion of this moisture is precipitated and the rest remains as moisture in the atmosphere. Papers by Anthes (1977) and Tiedtke et al. (1979) contain detailed descriptions of this type of system. Another approach, proposed by Arakawa and Schubert (1974), is similar to the Manabe et al. (1965)

scheme but also recognizes the fact that clouds entrain environmental air through their sides and detrain cloud air at the top. The heating and moistening of air are considered to be net effect of entrainment, detrainment, and the convectively induced subsidence of environmental air. Convection occurs instantaneously when clouds are destabilized. Krishnamurti et al. (1980) and Lord (1982) obtained encouraging results from the last two methods, based on observed data. There is, however, a general sensitivity of simulated convection to the selection of parameterization schemes. In addition, the above schemes consider neither the importance of downdrafts in deep convection nor the countergradient flux of momentum generally encountered in intense, organized convective systems. The parameterization of convection is still a major research area in GCM development because of the uncertainty in precipitation estimates, particularly for small regions, using GCMs.

The treatment of nonconvective precipitation is generally simpler in the parameterization scheme. It requires the estimation of other processes that can change the temperature and water vapor content, and involves computation of the amount of condensation of water vapor necessary to keep the relative humidity below a fixed threshold value. In the simplest case, all condensed water is allowed to precipitate. In more sophisticated treatments, the evaporation of precipitation may also be taken into account.

The strengths and weaknesses of GCMs

The GCMs are the highest level in a hierarchy of models that can be used for the study of climate. The various processes involved in climate are complicated and highly interactive. The hope for obtaining reliable quantitative results therefore more probably comes from the GCMs than from the other less comprehensive approaches. In fact, the GCMs can be considered as 'surrogate laboratories' for the climate system. They are the only available means to contain, simultaneously, representations of the important processes that affect climate.

The GCMs are far from being perfect. One major problem lies in their inability to represent climate processes well enough so that departures from the real situation, either in the numerical calculation or the physical formulation, will not expand to affect the final estimation. This is a problem because of the complicated interactions among the various processes and the prolonged numerical integration required to obtain the final GCM results. Another problem is the large computing time necessary for GCM runs. The CPU time for a GCM run estimating the effects of a doubling of CO_2, on the fastest of the current generation of computers, is in the order of months. In addition, GCM runs of climate modelling are essentially on a global scale. This, together with the high computational cost, means that running GCMs with a much higher resolution for regional climate simulations is not economically feasible at this stage. One estimate involves a 10-fold increase in computing time for a doubling of grid points in a GCM (Lorenz 1974).

In the above brief review of climate models, only the physical models are discussed. These are models that employ the basic principles of physics that govern the various components of a climate system. There are other approaches for modelling climate. A noticeable alternative is statistical modelling. An important concept associated with the use of statistical methods in climate modelling involves the fact that past and present states of the climate system hold the key to any future evolutions.

Climate prediction, using the statistical approach, involves first the identification of an appropriate model based on existing data and then extrapolation using that model to obtain a future situation. The statistical modelling of climate, if successful, would be useful for interpolation within the range of data from which the model was developed or for very short-term extrapolation outside the original data range. It would not be useful for such applications as estimating the enhanced greenhouse effect caused by the doubling of atmospheric CO_2 because the model developed would be inconsistent with the situation in which it was applied.

Comparisons of three GCMs for the estimation of normal ($1xCO_2$) climate

In this section, the performance of three GCMs in the simulation of Alberta's normal climate are examined. In the context of this study, normal climate refers to the observed 30-year normals for 1951-1980. The GCMs are those of the Oregon State University (OSU; Schlesinger and Mitchell 1987), the Goddard Institute for Space Sciences (GISS; Hansen et al. 1984) and the Geophysical Fluid Dynamics Laboratory (GFDL; Manabe and Wetherald 1987). The ability of these models to simulate present climate was assessed by comparing observed normals with the $1xCO_2$ model results. A summary of model characteristics is shown in Table 2.

Several consideration related to comparisons of model outputs and observed data must be taken into account. First, the model resolutions typically involve several degrees of latitude and longitude. The variables calculated for a specific grid point are, at best, average values over the grid. With such crude resolutions, details such as orography and surface conditions are represented in a general way that may in-

Table 2. General characteristics of the three GCMs.

	GIS	GFDL	OSU
Horizontal domain; Coordinate	Global; latitude-longitude	Global; latitude-longitude	Global; latitude-longitude
Vertical domain; Coordinate	Surface to 10 mb; sigma	Surface to 0 mb; sigma	Surface to 200 mb; sigma
Solution methods; - Horizontal resolution	Finite difference in vertical and time; horizontal 8 lat by 10 long	Finite difference in vertical and time; spectral in horizontal (15 truncation; 4.5 lat by 7.5 long)	Finite difference in vertical and time; horizontal 4 lat by 5 long
- Vertical resolution (layers)	9	9	2
Cloud influence on radiation	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer	Clouds are allowed to form in each layer; they affect albedo and IR radiative transfer
Insolation	Seasonal and diurnal cycles	Seasonal cycle	Saasonal cycle
Land/ocean distribution	Realistic	Realistic	Realistic
Topography	Realistic	Realistic	Realistic
Ocean	Mixed layer with seasonally varying depth; prescribed seasonal ocean heat convergence	Mixed layer is 50 m deep	Mixed layer is 60 m deep

fluence comparisons with data and other model results.

Second, the different models usually have different grid sizes, and historical climate data were collected over irregular networks. This means that point-by-point comparisons are not possible unless some form of interpolation is made. While interpolation for the relatively smooth temperature fields may be useful, the same cannot be expected of the much noisier precipitation fields. Even for a smooth spatial field like that of temperature, it is often difficult to determine whether any differences detected in the comparisons are due to the models or the interpolation scheme.

Third, it must be recognized that all the GCMs are different in terms of the details of the climate processes represented. There are also simplifications and approximations involved. For example, neither the OSU nor the GFDL models account for the effect of oceanic heat transport, whereas in the GISS model, meridional heat transport is prescribed in the atmosphere.

Finally, climate variability must be considered. Climate normals, which are usually computed over a 30-year period, vary as time proceeds. GCM outputs are obtained after the model run has attained near equilibrium status using prescribed atmospheric and oceanic conditions. Equilibrium conditions also vary between models. The results from the GFDL, GISS, and OSU models are the averages of the last 10 years of runs from, 35, 35, and 20 years of model time respectively. Other models may involve different averaging periods and take more or less time to reach a state of equilibrium.

Despite these various problems, the GCM estimates of the $1xCO_2$ climate conditions were compared with the observed climatic normals for Alberta in an attempt to provide some guidelines for assessing the usability of GCM results for regional impact assessments. This also provided an estimate of the magnitude of errors one might encounter in similar GCM applications. In subsequent sections, we will show how GCM results are used in the estimation of $2xCO_2$ effects. Such usage stresses the ability of GCMs to simulate the anomalies due to CO_2 doubling rather than to simulate equilibrium climates.

The data description

The outputs from the GISS, GFDL, and OSU GCMs for temperature and precipitation were extracted for those grid points in Alberta. These were compared with observations obtained from conventional AES stations for the period 1951-1980. The locations of the grid points and stations are shown in Figure 2. The stations used are listed in Table 3. The number of grid points and stations are summarized in Table 4.

Table 3. AES stations used in computing the observed normals of Alberta.

Banff
Calgary Int'l A
Cold Lake A
Coronation
Edmonton Ind'l A
Edmonton Int'l A
Edmonton Namao
Edson
Fort Chipewyan
Fort McMurray
Grande Prairie A
High level A
Jasper
Lethbridge A
Medicine Hat
Peace River A
Pincher Creek A
Red Deer A
Rocky Mountain House
Slave Lake A
Suffield A
Whitecourt A

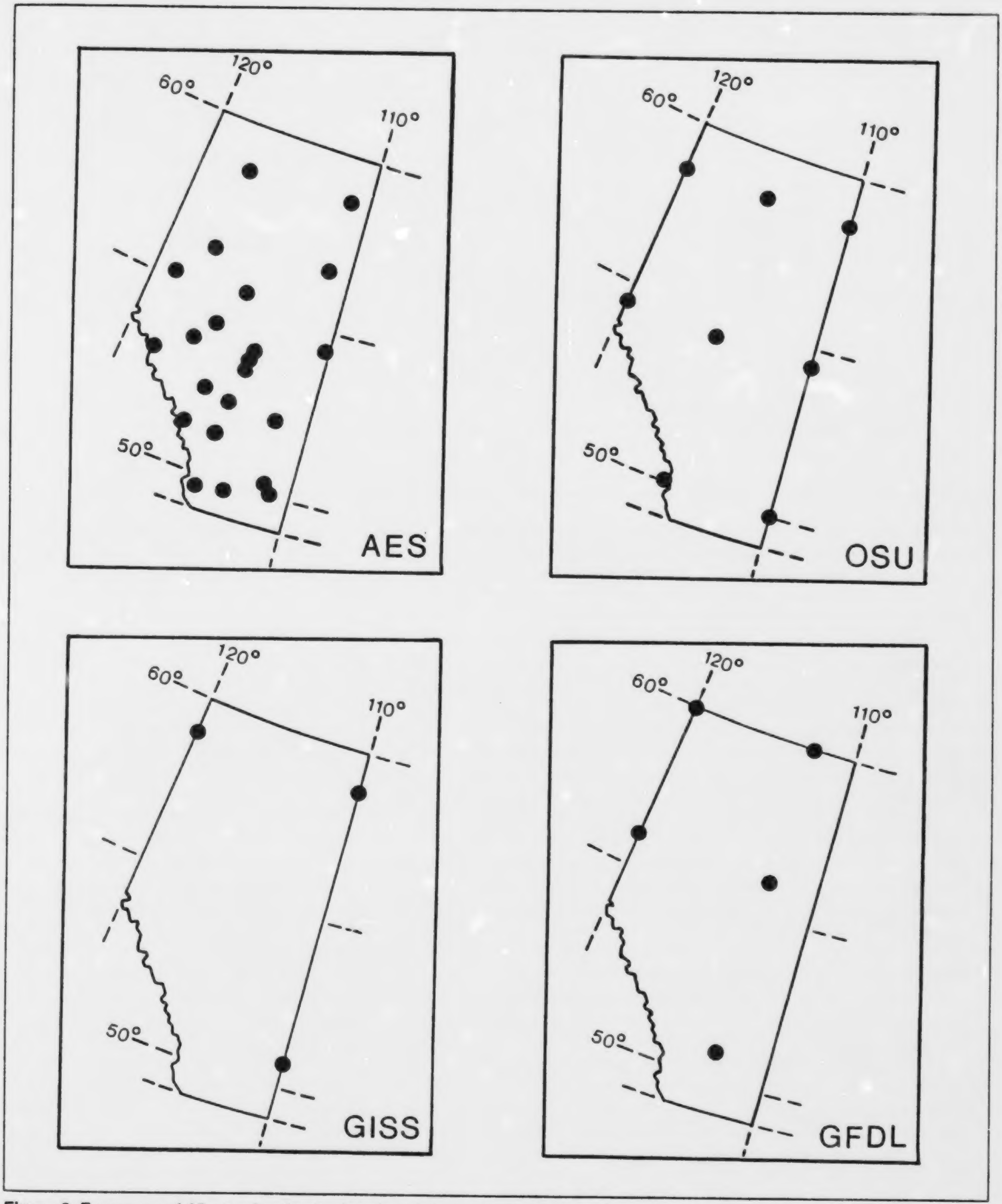


Figure 2. Four maps of Alberta showing the location of the Atmospheric Environment Service, Environment Canada (AES) weather reporting stations in Alberta and the grid points of estimated mean temperature and daily precipitation values for the OSU, GISS, and GFDL atmospheric models.

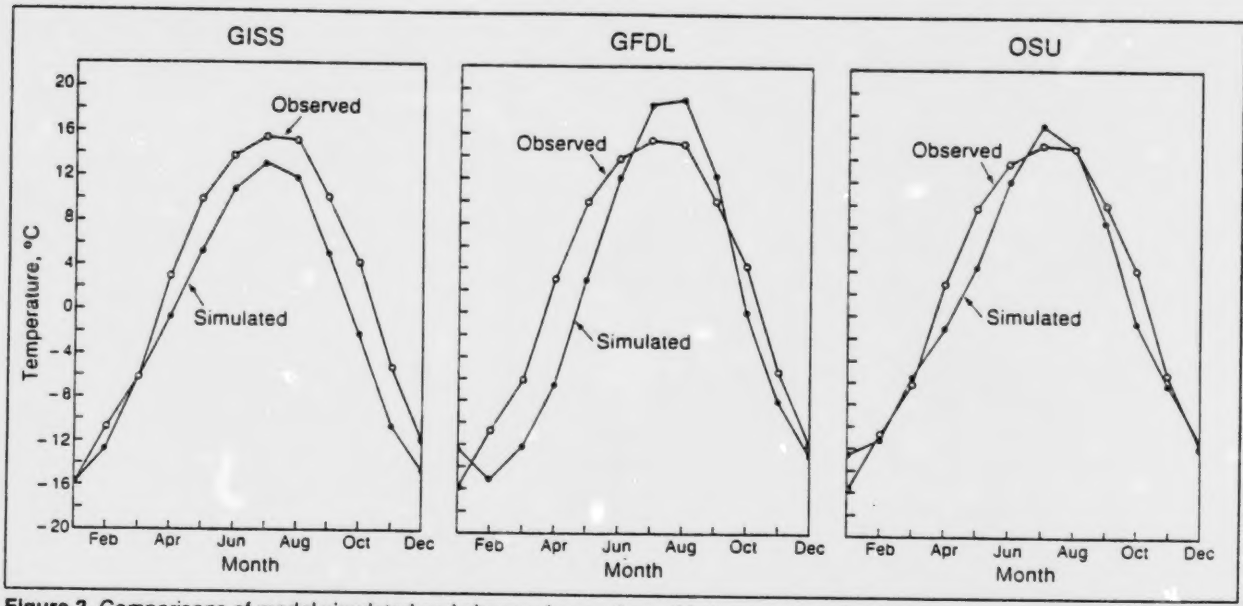


Figure 3. Comparisons of model simulated and observed normal monthly temperatures for Alberta.

The ability of these models to generate the annual cycles of temperature and precipitation under normal ($1xCO_2$) climate conditions was examined. Since the GCMs use different grid systems, the number of grid points for Alberta differs from model to model. The average monthly temperature (°C) and precipitation (mm/day) were computed with the available grid points for each model and compared against the normals obtained from the AES stations. Note that the simple arithmetic average is only a first approximation. In subsequent analyses more accurate representations of climate conditions may be attained by weighting of the data points according to the areal coverage or interpolation of station values to grid point locations. the problem of data "cleaning" and adjustments for bias caused by urban warming are discussed in the section on analysis of Alberta's climate data. These factors should also be considered in more thorough data-model comparisons.

Results of temperature comparisons

The results of the present temperature comparisons are presented in Figure 3. In each of the figures, the GCM average outputs are plotted against the observed average climatic normals. Note that the GCMs were able to reproduce the annual cycle, but the agreement is not perfect. The GFDL model shows a shift in both the annual maximum and minimum temperatures and an overestimation of the July to September monthly means. The temperatures for the other months, however, are underestimated with the exception of January. The GISS outputs underestimate temperatures by approximately 3 to 5°C for the period April to December, but provide reasonable agreement for the other three months. The OSU outputs show an underestimation for the months April to June and September to November, and a slight overestimation for August and January. The time of the year of the maximum and minimum temperatures were simulated quite accurately in both the GISS and OSU models.

Table 4. The number of grid points or stations.

	GISS	GFDL	OSU	AES
All Alberta	3	5	8	22
Northern Alberta	2	4	3	6
Southern Alberta	1	1	5	16

A more quantitative indication of the level of agreement was determined by calculating the mean absolute error (MAE) for each model-observation comparison. The MAE represents the average absolute difference between model estimates and observations; smaller MAEs signify better agreement. Two other measures that were computed are the correlation coefficient and the index of agreement. The use of these two measures for model evaluation are discussed by Fox (1981) and Willmott et al. (1985). Basically, the correlation coefficient measures the degree of linear association. It must be used in association with the MAE for a description of agreement. The index of agreement was meant to be an improvement over the correlation coefficient and MAE, as it represents both magnitude of error and linear association. The value of the index of agreement can vary between zero (for complete lack of agreement) and one (for perfect agreement). There are two methods for computing the index of agreement (see Willmott et al. 1985 for details). The one used here has an exponent

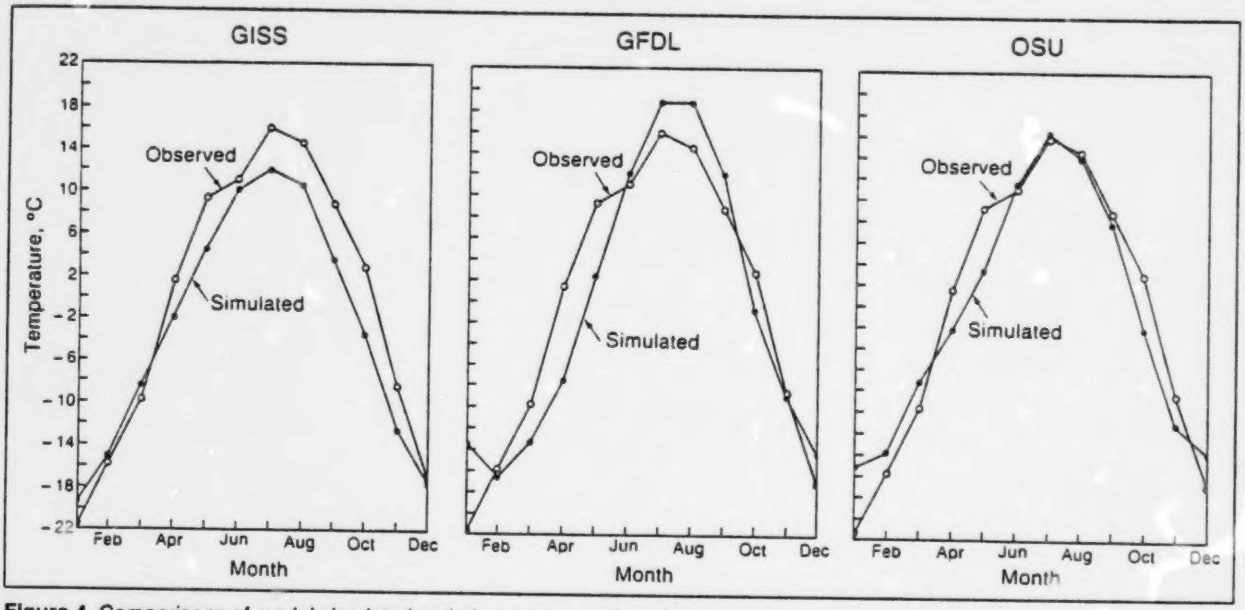


Figure 4. Comparisons of model simulated and observed normal monthly temperatures for northern Alberta.

of one for greater resistance to outlier effects. The results are shown in the upper portion of Table 5. Also included are the results of the two subsamples for northern and southern Alberta, these two regions being divided at latitude 55 degrees north. The subsamples represent a further reduction in the number of grid points from GCMs, which signifies a further increase in the uncertainty of the results. The subsample results can be compared with those for all Alberta.

Table 5 shows that the correlation coefficients of observed and simulated temperature values are quite high, and the subsample results are comparatively good relative to the values for the whole province. The same can be said of the index of agreement. Figures 4 and 5 show these relations for the subsamples, and a comparison of these figures to Figure 3 (the values calculated for the province as a whole) demonstrates the similarities between the three regions. The high correlation is not unexpected because of the predominating effect of the annual insolation cycle on temperature trend. More emphasis should be placed on the MAE as an evaluation parameter. In general there is a lower correlation and index of agreement for the GFDL model temperature results. In addition the MAEs for temperature values obtained from the GFDL model are higher.

Results of precipitation comparisons

The comparisons of average Alberta precipitation for each month are summarized in Figure 6. The agreement is generally not as good as that for temperature, reflecting the more noisy nature of precipitation fields and the greater uncertainty associated with the modelling of precipitation processes in GCMs.

Note that although the GFDL model could reproduce the precipitation maximum in June, it did not accurately simulate the annual precipitation cycle (Figure 6). The predicted existence of a secondary maximum in February does not occur in actuality. On the other hand, the GISS model appears to simulate the annual precipitation cycle well, but the estimates

Table 5. Comparisons of GCM results with observations of normal climate.

	All Alberta			North Alberta			South Alberta		
	GISS	GFDL	OSU	GISS	GFDL	OSU	GISS	GFDL	OSU
GCM temperature comparisons									
MAE	3.21	4.10	2.37	3.08	3.86	2.78	1.93	3.29	2.34
Correlation	0.99	0.94	0.97	0.99	0.93	0.97	0.97	0.93	0.96
Index of agreement	0.83	0.81	0.88	0.86	0.83	0.87	0.88	0.82	0.87
GCM precipitation comparisons									
MAE	0.93	0.83	0.63	0.90	0.84	0.49	1.24	1.04	0.74
MAE/mean	0.76	0.68	0.52	0.77	0.72	0.42	1.10	0.92	0.65
Correlation	0.92	0.67	0.35	0.90	0.51	0.34	0.83	0.80	0.24
Index of agreement	0.37	0.40	0.28	0.36	0.37	0.27	0.30	0.34	0.33

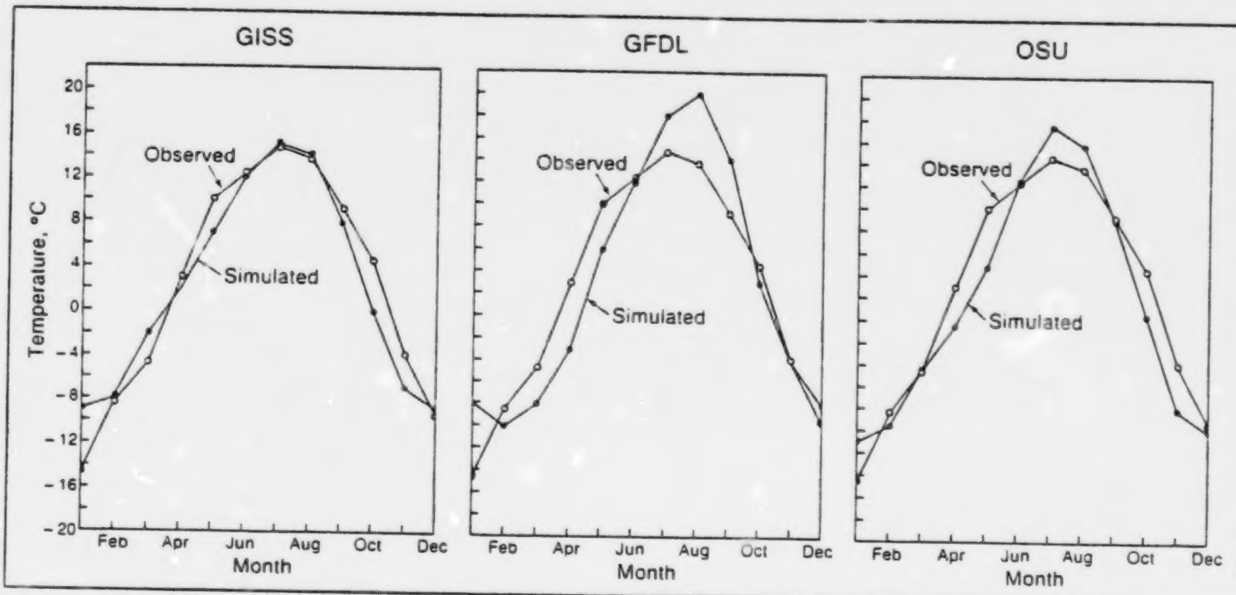


Figure 5. Comparisons of model simulated and observed normal monthly temperatures for southern Alberta.

are consistently higher than observed values. The outputs from the OSU model underestimate precipitation for the summer months (June to September), and overestimate for the rest of the year, although both estimated and observed precipitation maxima occur in June.

The MAEs, correlation coefficients, and indices of agreement for comparisons of precipitation are shown in the lower portion of Table 5.

As an added measure, the ratio of the MAE to the mean was also computed for each case. The MAEs for precipitation are 0.93, 0.83, and 0.63 mm/day for the GISS, GFDL, and OSU models, respectively. Compared to an annual mean of 1.22 mm/day, these values represent rather large overall errors 76, 68, and 52% respectively, for the three models. As with temperature, the results for the subsamples Figures 7 and 8 are similar to those for the province as a whole (Figure 6), with the exception of a few details. The subsample results are also shown in the lower portion of Table 5. Unlike the situation with temperature, the precipitation results show a general increase in uncertainty for the subsamples. This is a result of the dominance in the temperature data of the annual insolation cycle that is represented in the GCMs.

Observations

From the above analysis, there are several observations regarding the use of GCMs as tools for providing climate information for strategy development in Alberta.

1. It is obvious that for a region the size of Alberta, the GCM-generated normal climates conditions are often different from observed conditions. The same error will probably occur for other generated climate scenarios. The fact that the agreement between observed and predicted results is much less for precipitation than for temperature implies that for many practical applications, the results will be dominated by errors in the precipitation estimates. For applications such as water balance or drought index computation, the error in precipitation estimates will be a major source of error.
2. According to Willmott et al. (1985), the error in model results can be divided into two parts: systematic and nonsystematic. The systematic part represents error that can be adjusted through model improvement or statistical relationships. The correlation between predicted and observed precipitation for the GISS model (Figure 6), for example, is 0.92. The error decomposition gave an estimate of 90% for the systematic error and 10% for the nonsystematic error. This implies that the GISS estimates of average precipitation can be significantly improved by establishing a relationship between model outputs and the values observed. The applicability of such a relationship, however, will likely be restrictive because it will not hold in other situations such as a doubling of atmospheric carbon dioxide. Users of GCM results should be aware of the importance of such assumptions whenever relationships are derived and applied.
3. So far, only the averages of surface temperature and precipitation have been examined. Surface temperature and precipitation are only two of the many parameters computed by the GCMs. It may appear unreasonable to judge GCM performance by the agreement between the observed and predicted results of only two variables. These two

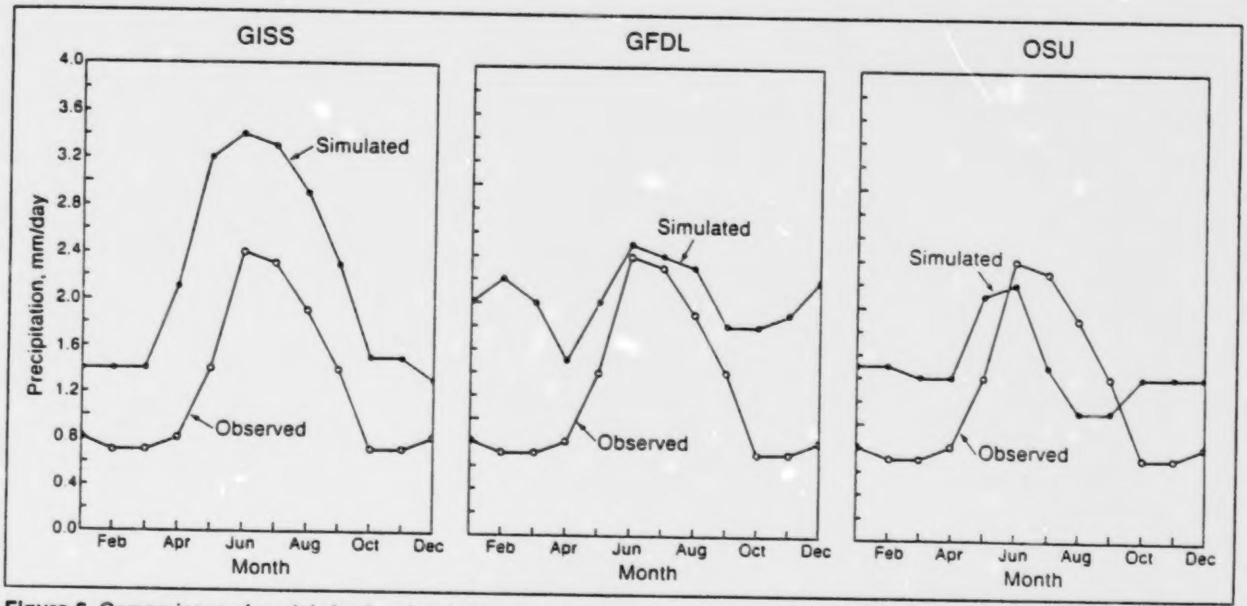


Figure 6. Comparisons of model simulated and observed normal monthly precipitation for Alberta.

parameters, however, are the most important for assessing climatic impacts and for developing strategies. For an initial assessment of GCMs, accurate representation of surface temperature and precipitation is an appropriate criterion. Subsequent analysis should include wind and other climatic parameters.

4. The interested user may wonder if the results from the different models can be combined. For example, the MAEs listed in Table 5 for southern Alberta suggest that the GISS model temperature results were more accurate, as were the OSU model precipitation results. In this sense, it appears logical to use GISS temperature and OSU precipitation results for the southern Alberta region. Such a mixture is not recommended, however, because it gives no consideration to the physical relationships between the parameters. The strength of GCMs lies in their sophisticated representation of such relationships, which provide a guideline for the internal consistency of results.

In summary, we have compared the GCM outputs for 1xCO_2 with the observed normals for Alberta's temperature and precipitation patterns in an attempt to assess the usefulness of GCMs as a source of climate information. It was shown that for a small region like Alberta, the GCMs are unable to provide accurate estimates of normal surface temperatures and precipitation, although they were calibrated with the normal climate on the larger (global/hemispheric/zonal) scale. An overview of the annual mean temperature and total precipitation estimates by the GCMs are shown in Table 6. Apart from the large discrepancies in precipitation it is interesting to note that all three GCMs yielded greater amounts of precipitation for southern Alberta than northern Alberta; this is the opposite of what is observed. From such analysis, it is indicated is that GCM estimates of equilibrium regional climate may not be realistic.

A major difficulty with regional application of GCMs is resolution. There are simply not enough grid points in the GCMs to represent Alberta. Apart from the lack of detail, as mentioned previously, the small number of grid points also means small sample sizes from the estimated fields, where biased results would likely be obtained. Grotch (1988) suggests that in order to obtain significant agreement between model-simulated and observed results, one must consider an area containing more than 20 grid points. Assuming that the same argument holds true in the reverse direction, one should have at least 20 and probably more grid points in Alberta for a reasonable GCM result. The computing requirements for such a GCM are still prohibitively high. In addition, the number of grid points required for stable estimates is probably dependent upon the parameter considered. For example, one

Table 6. Overall comparisons of GCM simulation and observations.

	GISS	GFDL	OSU	Observed
Mean Temperature (C)				
All Alberta	-1.48	-0.22	0.42	1.73
S. Alberta	1.92	2.67	1.38	2.21
N. Alberta	-3.17	-0.93	-1.16	-0.79
Total Precipitation (mm)				
All Alberta	781.7	748.3	547.5	416.1
S. Alberta	863.9	790.6	614.4	412.5
N. Alberta	757.4	733.0	450.2	427.5

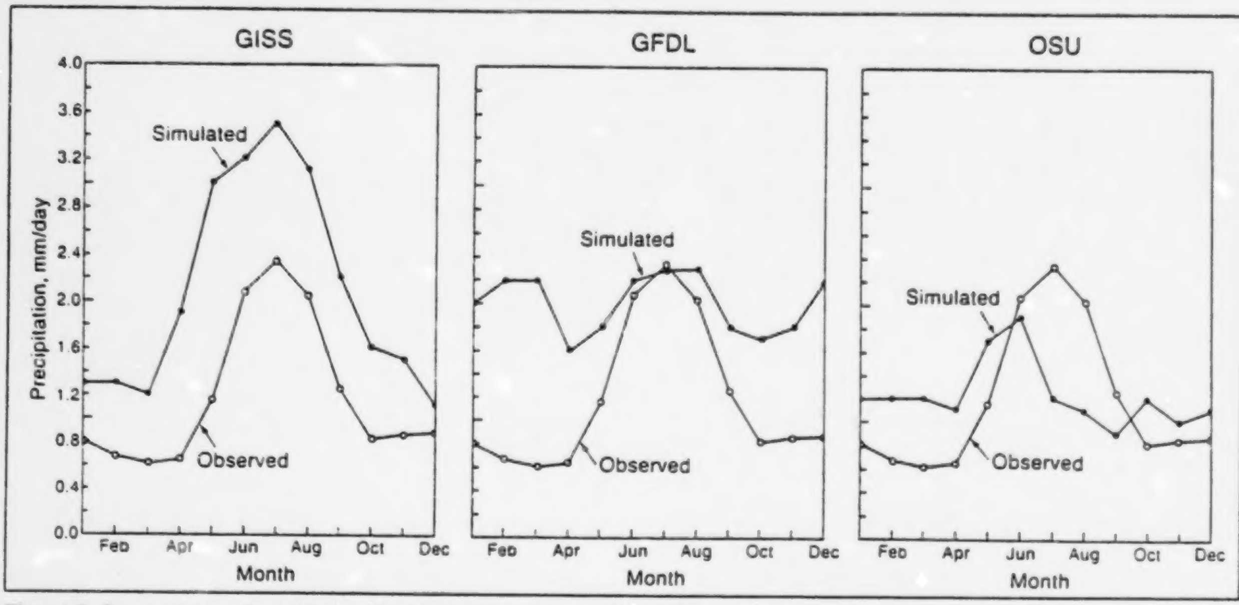


Figure 7. Comparisons of model simulated and observed normal monthly precipitation for northern Alberta.

would require more points for a noisy field like that of precipitation than a smooth field such as pressure.

Alberta under a 2xCO$_2$ scenario

Are GCM simulations useful for strategy development in Alberta?

There are two types of climate prediction described by Lorenz (1975):

1. The first is a prediction of how the weather statistics defining climate change as a function of time. Because theory says that there is a limited predictability of weather conditions (i.e. one cannot forecast weather beyond a limited period of time), one cannot expect much skill in climate prediction of this kind.
2. The second involves prediction not directly related to the chronological order of the atmospheric states. Instead it is associated with such topics as the status of the climate if C0$_2$ levels doubled. The main use of GCMs is with this type of climate prediction. Considering the poor reproduction of the normal regional climate described previously, one may ask if the 2xCO$_2$ climate estimated by the GCMs are usable for strategy development in Alberta? The answer to such a question is not as clear cut as one would like. One must consider the value of the climate forecast and how GCM results are used. It has been suggested that the words "simulation" or "scenario" instead of "prediction" be used for GCM results. This stresses the fact that GCM results are not predictions in the usual sense of the word.

Rasmusson (1987) states that the value of a forecast depends on three factors: (a) the quality of the forecast, (b) the needs of the user, and (c) the knowledge on the part of the user as to how the forecast should be used. The usability of GCM results depends on the interplay of these three factors in each case.

The quality of the forecast

The quality of GCM forecasts is generally poor for regional applications. GCMs are the best available tools for estimating future scenarios of climatic warming, yet one encounters considerable uncertainties in GCM results. Such uncertainties exist even for areas much larger than Alberta (Grotch 1988). On a smaller scale, Cohen (1989) used several GCMs to study the projected changes in the water resources of the Saskatchewan River sub-basin due to greenhouse warming. The sub-basin is approximately half the size of Alberta, and conflicting results were obtained using scenarios derived from different GCMs. One explanation involves the poor representation of precipitation caused by an insufficient number of grid points and sparse observation for the headwater regions of the sub-basin. There is no doubt about the scientific validity of GCMs, but science has not advanced to the level that such uncertainties can be effectively reduced. This means that the best available tools are still not as good as one would like them to be.

The needs of the user

There are many users of GCM results for regional climate impact assessments, and therefore there is a the strong need for regional climate information. It is important to consider both the tolerance level of the

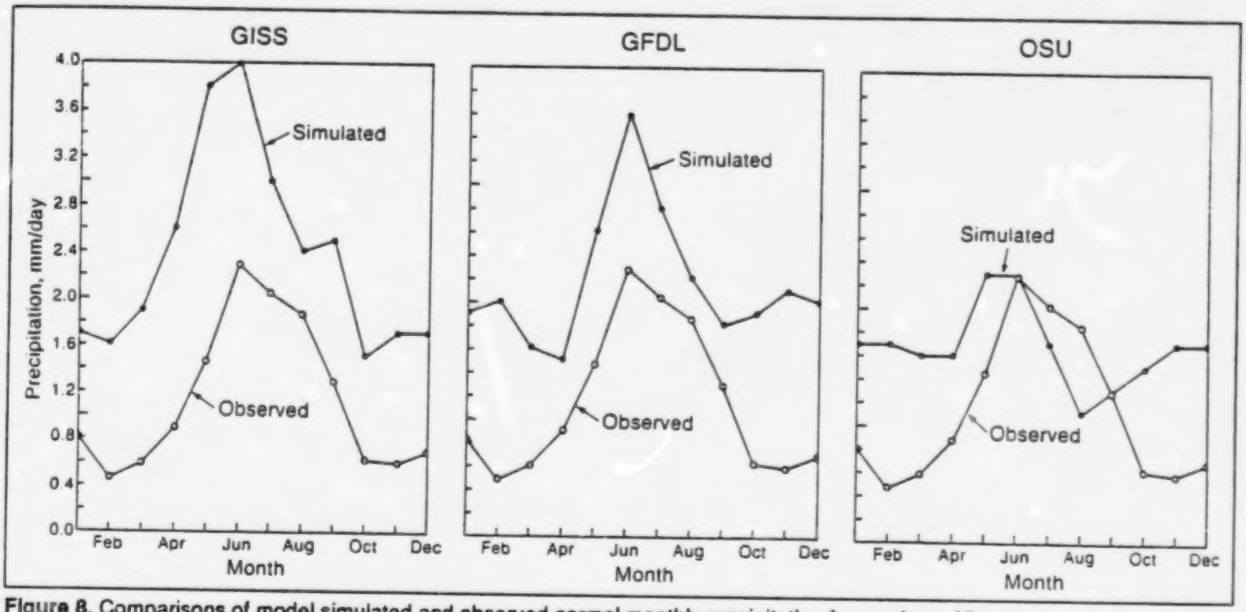


Figure 8. Comparisons of model simulated and observed normal monthly precipitation for southern Alberta.

users to errors in the climate forecast and the desire of the user to extract useful information from the available forecasts. GCM forecasts are therefore very user-specific because the requirements of users vary considerably. For example, some users can use a qualitative indication of the direction of change in a single parameter, whereas others require a quantitative prediction of several parameters.

The knowledge of the user

The knowledge of the user concerning the weaknesses and uncertainties of GCM results is also important. The users of GCM simulations for regional assessments should recognize that the results contain some uncertainties; this must be stressed for all conclusions. It was once suggested that this situation is analogous to that of a dirty crystal ball. Some would prefer cleaning it before looking inside to see what it says; others would try to see first rather than waiting for the cleaning.

For users of GCM results, the GCM simulations should be considered as estimates of possible future states of the climate system rather than actual forecasts of what the future state will be. For this reason, one should examine the results based on outputs from a number of GCMs and consider them all as possible outcomes, i.e. it is advisable to compare outputs from more than one GCM.

Following is a description of how GCM results are used in the simulation of enhanced greenhouse warming under $2xCO_2$ conditions. It is generally believed that, although the long-term climate simulated by a GCM may differ from observed conditions, the anomaly associated with CO_2 doubling may be more realistic (Kim et al. 1984). The usual practice is to obtain simulations of equilibrium climates from the $1xCO_2$ and $2xCO_2$ runs. For surface temperature, the degree of warming at each location is calculated by subtracting the $1xCO_2$ from the $2xCO_2$ results. The increment in monthly temperature thus obtained is added to the normal observed temperature for an estimate of the projected change. For precipitation, the percentage change in precipitation under $2xCO_2$ conditions is computed using model results, and the resulting ratio is multiplied by the normal observed precipitation to obtain an estimate of the projected change in precipitation. This implies a greater confidence in the GCM results for estimating the amount of change under $2xCO_2$ conditions than in the actual GCM-generated $2xCO_2$ climate. It is impossible to assess the errors associated with such estimates of anomalies, relative to the errors associated with estimates of the equilibrium normal climates. The fact that these are simulated possible outcomes or scenarios rather than forecasts should be emphasized.

Climate scenarios for Alberta

Projection of current trends suggest a doubling in atmospheric CO_2 concentration from preindustrial levels by 2030 to 2050 A.D.. The GCM estimates for a $2xCO_2$ climate in Alberta are presented in Figures 9 to 14. These are possible outcomes or simulated scenarios under CO_2 doubling conditions. The results from all three GCMs are included.

Figure 9 shows that the GCMs estimate a general warming trend for Alberta, although the degree of warming differs from model to model. In general the GFDL model predicted the greatest amount of warming, the OSU model estimated the least, and the GISS

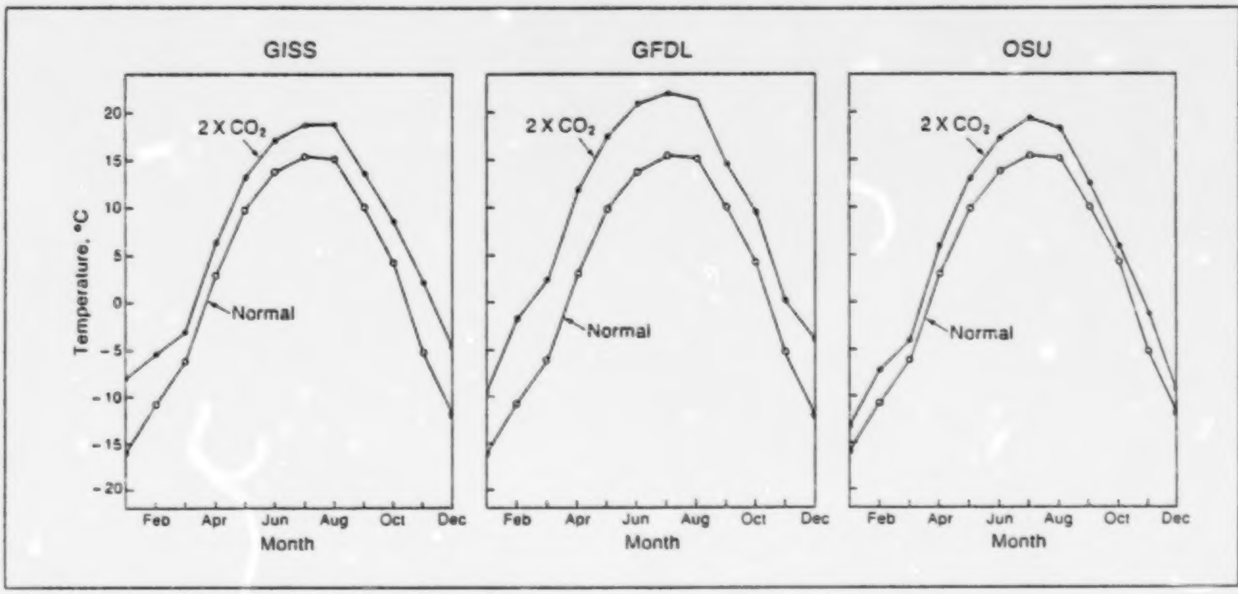


Figure 9. Model projections of $2xCO_2$ effect on the monthly temperature of Alberta.

model gave intermediate results. The overall warming levels are shown in Table 6. Note that the GISS model showed the greatest warming during November to January, February to April for the GFDL model, and February, June, and July for the OSU model. Similar differences were observed for the northern and southern Alberta subsamples (Figures 10 and 11).

Table 7 also lists the changes in precipitation under $2xCO_2$ conditions. All models estimated a general increase in total annual precipitation for Alberta, with greater increases in the northern part of the province than in the southern part. The results from the models do not agree on the actual amount or distribution of change. The latter is shown in Figures 12 to 14. Note that while the GISS model did not simulate any decrease in precipitation for any particular month, both the GFDL and OSU models show varying distributions of increases and decreases in precipitation throughout the year. Similar patterns exist for the subsamples.

Climate variability under $2xCO_2$

Evaluators of the impacts of climate change often require information on climate variability. There is, however, a lack of accurate estimates on how variability changes under $2xCO_2$ conditions. The GCMs can provide some information but it cannot be used without some assessment of how well the model-generated variability agrees with observed climate data.

Rind et al. (1989) is the first systematic study of GCM-generated estimates of climate variability under $2xCO_2$ conditions. A statistical study of the GISS GCM outputs for the United States, it made use of the standard deviations for temperature and precipitation as measures of climate variability. Because the study was based on the actual GCM-generated climate (rather than the GCM-generated anomaly) the results directly reflect the uncertainties inherent in the models. Based upon a series of statistical tests, however, the authors were able to identify certain trends in the results. These include a decrease in the year-to-year temperature variability and in the extremes in the daily temperature variability. Annual precipitation variability tends to increase.

There are other difficulties associated with deducing climate variability information from current GCMs. Variability may be affected by processes not simulated in the GCM experiment. For example, the $2xCO_2$ runs do not simulate El Nino, a phenomenon affecting interannual climate variability. In fact, El Nino effects cannot be well-simulated without significant improvements in the representation of ocean dynamics in coupled ocean/atmosphere models, presently a major thrust of research. In addition, GCMs do not include small-scale weather disturbances such as hurricanes and tornadoes, which are important factors of variability but are too small for the models to resolve.

Table 7. Overall $2xCO_2$ estimates from GCMs.

	GISS	GFDL	OSU
Temperature increase (°C)			
All Alberta	4.7	7.0	2.9
N. Alberta	4.7	7.1	3.2
S. Alberta	4.6	6.2	2.8
Precipitation increase (%)			
All Alberta	28	15	7
N. Alberta	32	18	8
S. Alberta	18	7	7

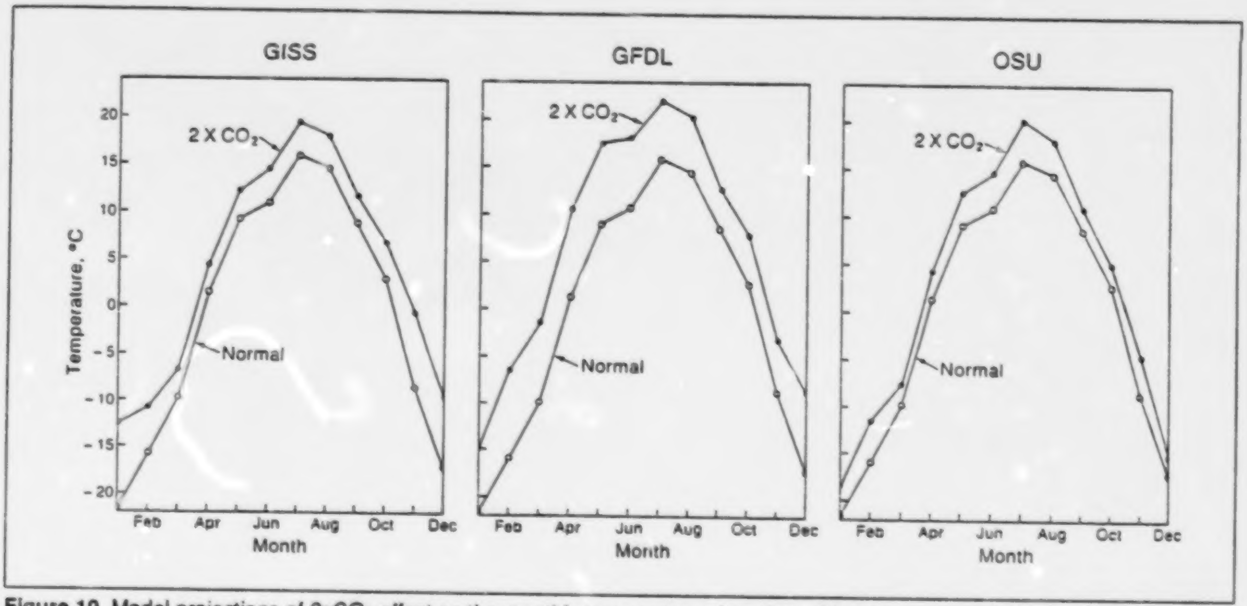


Figure 10. Model projections of $2xCO_2$ effect on the monthly temperature of northern Alberta.

Improved simulation/application techniques currently under development

The problems with results from currently available GCM simulations, noted in the previous two sections, are well known and a number of efforts are currently underway to address these problems.

The limited resolutions now possible in GCM simulations will be remedied to some extent with the advent of faster and more efficient computers. Such computers will allow substantial increases in the number of grid points used in simulations, thereby increasing the resolutions for regional applications. Faster and more efficient computers will also allow more realistic parameterizations and more accurate mathematical representations of physical processes, reducing the extent to which reality must be approximated in order to solve the equation. Thus, the accuracy of GCM simulations should improve with time.

In the meantime, GCM outputs can be made more applicable for regional problems by interpolating results at the currently available grid points to give intermediate grid points, thereby increasing the resolution. This is referred to as the 'climate inversion' problem because it is the reverse of the problem of parameterization in climate models. Apart from simple interpolation schemes, some success has been reported using statistical techniques such as empirical orthogonal functions in areas with strong surface climatic controls, e.g. mountains, water bodies, etc. (Kim et al. 1984). Applicability of such methods to Alberta should be examined.

A more sophisticated method of applying GCM simulation results to regional problems is the use of regional climate models. These are small-scale climate models with some form of linkage to large-scale simulations. Examples of such linkages include various degrees of coupling to a GCM, and telescoping grid elements for zooming onto a small region for detail while maintaining sufficient global coverage. Regional climate modelling is an active area of research (e.g. the limited area climate model of the National Centre for Atmospheric Research (NCAR) is to be published in Climatic Change), and the mesoscale meteorological models are being used for the climate inversion problem (Segal et al. 1982).

Summary

The most sophisticated climate models are the three-dimensional GCMs.

For economic reasons, a GCM usually has grid point spacing of several degrees of latitude or longitude and only a limited number of height levels. Processes smaller than those resolvable by the grid system must be parameterized. The parameterization of convection is still a major area of research in GCM development, and it is a cause of uncertainty in precipitation estimates, particularly for small regions.

The GCMs are the only available means to simultaneously represent the important processes that affect climate. They are, however, expensive to use and running them at a resolution appropriate for regional climate problems is not currently feasible.

An alternate approach involves statistical modelling, but this is appropriate only for interpolation within the

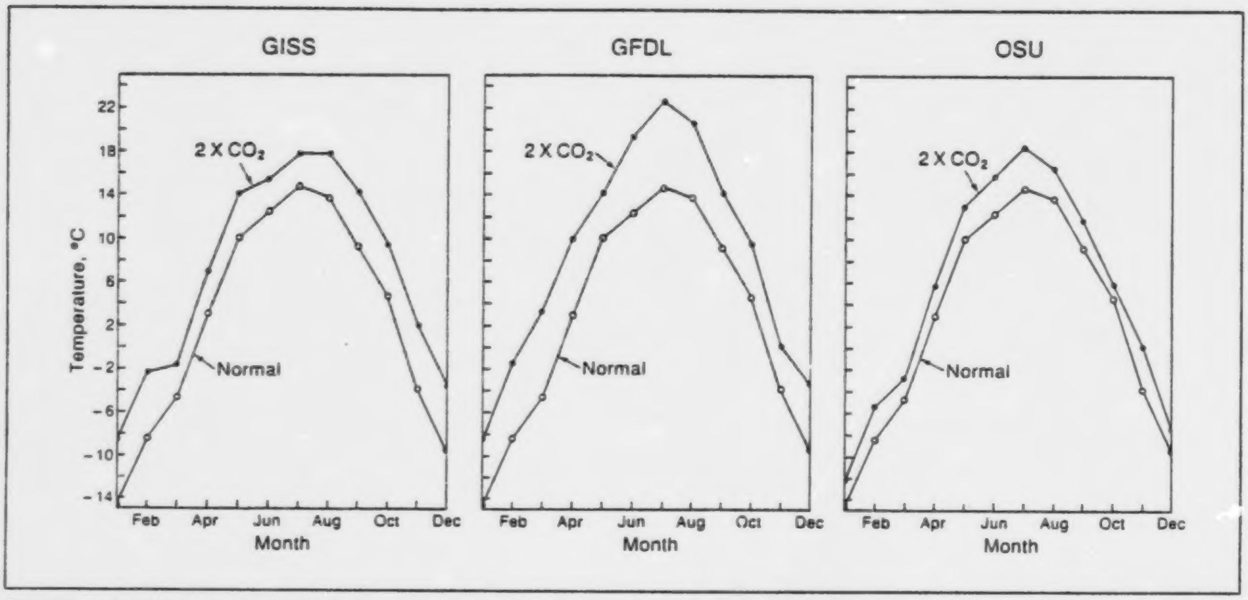


Figure 11. Model projections of $2xCO_2$ effect on the monthly temperature of southern Alberta.

range of data from which the model was developed or for very short-term extrapolation outside the original data range.

The performance of three GCMs in simulating Alberta's normal climate was investigated. This entailed comparing simulation results for a $1xC0_2$ scenario with Alberta's average climate from 1951 to 1980. Because results from GCM simulations are available only as parameter values at grid points, of which there are very few within Alberta, and climate data were collected over irregular networks, point-by-point comparisons are not possible unless some form of interpolation is used. While interpolation for the relatively smooth temperature fields may be useful, the same cannot be expected of the much noisier precipitation fields.

With respect to simulating Alberta's normal monthly temperatures, the GCMs were able to reproduce the annual cycle, but the agreement between predicted and observed was not perfect. An objective measure of the agreement between GCM results and normal Alberta climate values is given by the index of agreement which represents both magnitude of error and linear association; it ranges from zero (for complete lack of agreement) to one (for perfect agreement). For the temperature simulations, the index of agreement ranges from 0.81 to 0.88, suggesting that the GCMs' ability to simulate temperature is relatively good for all three models examined.

With respect to the simulation of the average Alberta precipitation by GCMs, the index of agreement ranges from 0.27 to 0.40, indicating that GCMs are poor simulators of precipitation. This is caused by the more noisy nature of precipitation fields and the greater uncertainty associated with the modelling of precipitation processes in GCMs. For many practical applications, results obtained from GCM simulations will be dominated by errors in precipitation estimates. All three GCMs predicted greater amounts of precipitation for southern Alberta than for northern Alberta, contrary to what actually occurs.

For some of the model results, a large part of the error appears to be systematic. This implies that the results can be improved by developing a relationship between model outputs and observed values. Such a relationship, however, may not hold for other situations such as a $2xCO_2$ scenario.

It appears that GCM simulations of equilibrium regional climate may not be realistic. Similar errors are probably inherent in GCM simulations of other regional climate scenarios (i.e. a doubling of atmospheric CO_2). Thus, users of GCM simulations should consider GCM results as estimates of possible future states of the climate system rather than actual forecasts of the future state. It is advisable to compare outputs from more than one GCM.

Although the long-term climate simulated by a GCM may not be realistic, the anomaly associated with CO_2 doubling may be more realistic. This implies a greater confidence in the GCM results for estimating the amount of change using a $2xCO_2$ scenario than in the actual GCM-generated $2xCO_2$ climate. It is impossible to assess the errors associated with such estimates of anomalies.

Projections of current trends suggests for a doubling in atmospheric CO_2 concentration from preindustrial levels by 2030 to 2050 A.D..

The results from all three GCMs suggest a general warming trend for Alberta, although the degree of warming differs from model to model (2.9 to 7.0°C); a

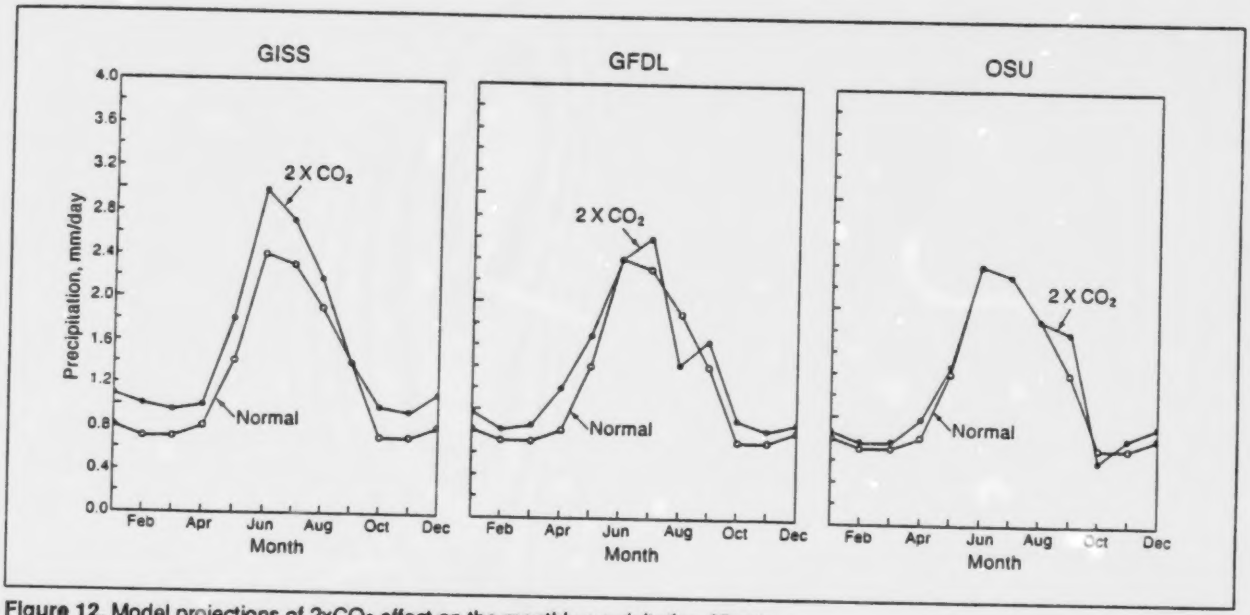


Figure 12. Model projections of $2xCO_2$ effect on the monthly precipitation Alberta.

significantly greater increase in temperature is implied in the northern part of the province than in the southern part. Some of the GCM results suggest decreases in precipitation in the summer months. It has been suggested that an increase in precipitation of 10% or more will be required to offset the increased evaporation due to warmer temperatures.

There is a lack of accurate estimates of the way in which climate variability change if atmospheric CO_2 were to double. The best estimates currently available suggest a decrease in the year-to-year temperature variability and an increase in annual precipitation variability.

The accuracy of GCM simulations will improve as faster computers and better parameterizations and mathematical models become available. Regional climate modelling is an active area of research.

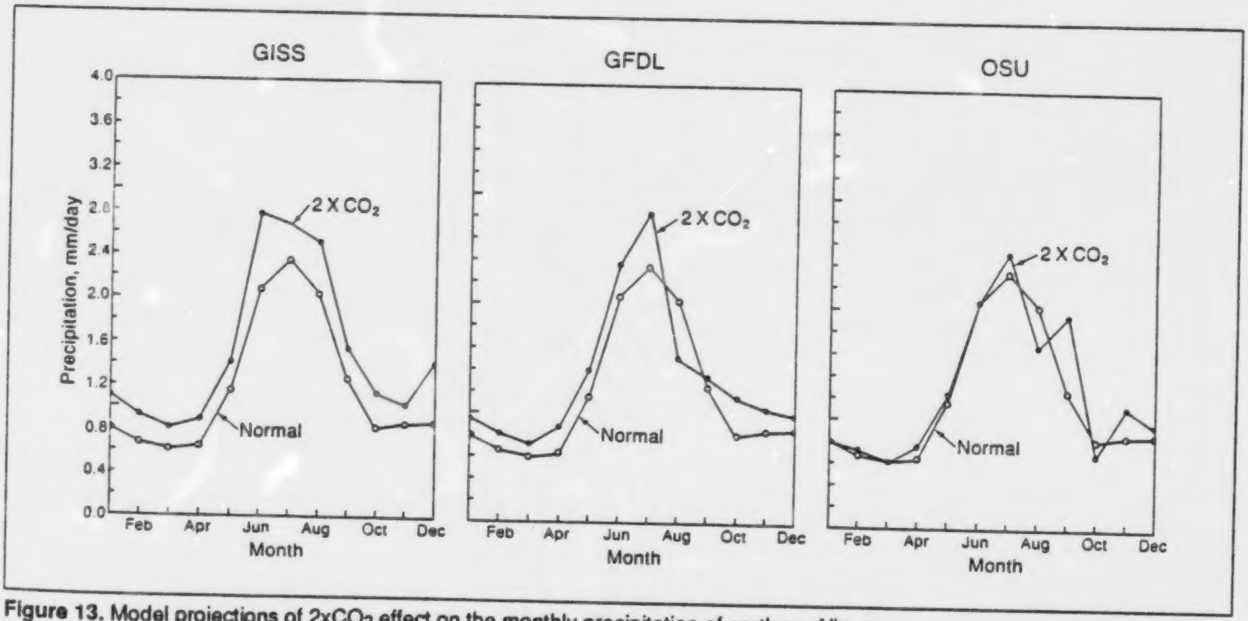


Figure 13. Model projections of $2xCO_2$ effect on the monthly precipitation of northern Alberta.

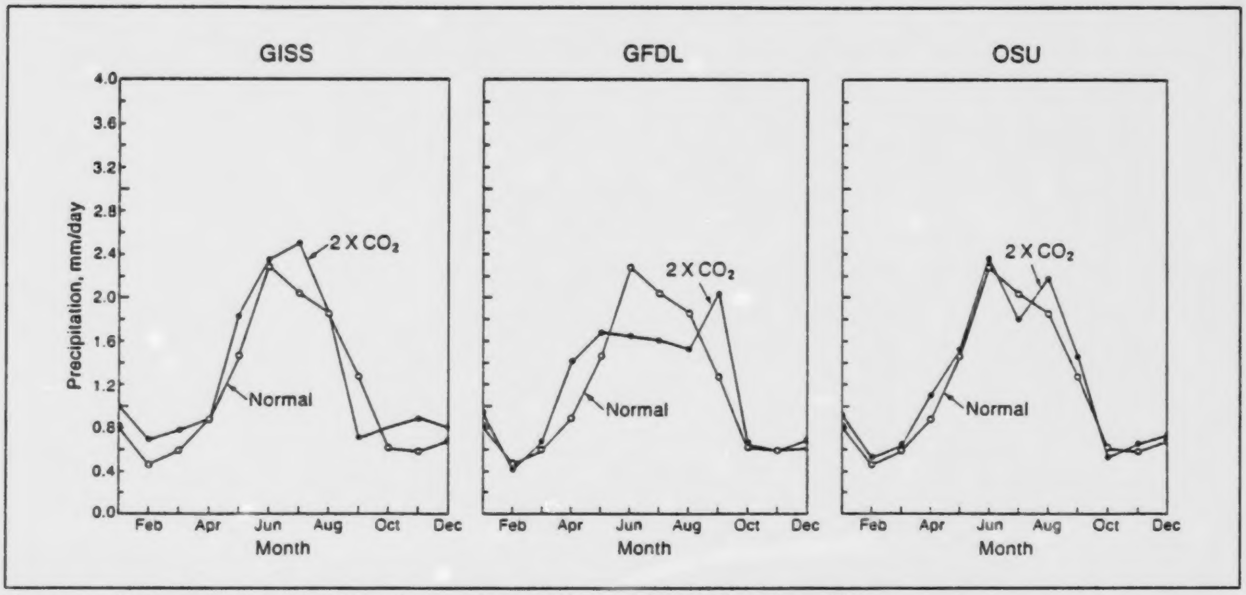


Figure 14. Model projections of $2xCO_2$ effect on the monthly precipitation of southern Alberta.

Analysis of Alberta's climate data

Introduction

The objective of this part of the study was to examine the climatological records of Alberta so as to detect any significant changes in climate parameters in recent years. The climate parameters examined in this study were temperature and precipitation. Longley (1972) was the first to provide an in-depth study of the climate of Alberta. Since then, various climate-related studies for Alberta have been carried out. A synthesis of these can be found in Papirnik et al. (1987, 1989). Most of the studies are concerned with a particular aspect of physical climatology such as rain, snow, hail, or lightning, or a particular application of climatological information such as agriculture, forestry, or hydrology. There have been no studies concerned with quantifying indications of climate change, particularly for the 1980s; therefore, emphasis in this part of the study is on a comparison of the climate of Alberta in the 1980s with that in the past.

Climate data and data adjustments

Historical records of Alberta's climate data gathered by AES were analyzed. Most of the observation stations are scattered throughout southern Alberta and many have climatic records for only short periods of time. The stations that are currently operating and have more than 37 years of data (1951-1987), encompassing the "normal" period 1951-1980, are shown in Figure 15. Different symbols are used to denote the length of time for the climatic records of these stations. For reference, major population centres are also plotted. The stations are listed in Table 8, and their records form the data base for the present study. Since the station selection criterion involved the existence of continuous records for at least 37 years prior to 1987, stations such as Pincher Creek, Fort Vermilion, Fort Chipewyan, Keg River, and Athabasca were not included. Figure 16 includes all the climate stations in Alberta. It can be compared with Figure 15 to identify the stations excluded from the analysis. The data from such stations should probably be reassessed. It may be possible to use more sophisticated data analysis procedures and less rigid data selection criteria in subsequent analyses. In the present study, surface temperature and precipitation measurements from the selected stations were examined. Since there are few stations in northern Alberta, the results shown for this area are based on simple extrapolations. This fact should be considered in interpreting the results. Essentially, no data was available for the area north of Fort McMurray and therefore, results shown for the more northerly locations are probably less meaningful.

In some cases, temporal nonhomogeneity in the data was caused by the relocation of the observational site (for example, the Rocky Mountain House station was moved to the airport in 1978). Figure 17 shows a

Table 8. Climate stations with more than 37 years (1951-1987) of records.

Banff
Caldwell
Campsie
Carway
Elk Point
Fort Macleod
Grande Prairie
Kananaskis
Lethbridge A
Medicine Hat
Ranfurly
Suffield
Beaverlodge
Calgary
Camrose
Coronation
Entrance
Fort McMurray
High River
Lacombe
Lethbridge CDA
Olds
Red Deer
Taber
Beaver Mines
Calmar
Cardston
Edmonton
Fairview
Gleichen
Jasper
Lake Louise
Manyberries
Pekisko
Rocky Mountain House

double-mass curve (Searcy and Hardison 1960) for the annual mean temperature of Rocky Mountain House and the nearby Olds station. The double-mass curve is a tool for detecting the change in proportionality between two highly correlated time sequences of observations. A change in proportionality such as that caused by the relocation of one of the stations is represented by a kink in the curve. This also permits one to estimate the adjustments required for data homogeneity. The observed temperature at Olds is well-correlated with that of Rocky Mountain House and was therefore used to construct the double-mass curve. There is a distinct kink in the double-mass curve at 1978, suggesting that station relocation had a significant effect on the data sequence. Temperature data for Rocky Mountain House after 1978 were therefore adjusted. Similar data adjustments were also performed for the Red Deer station.

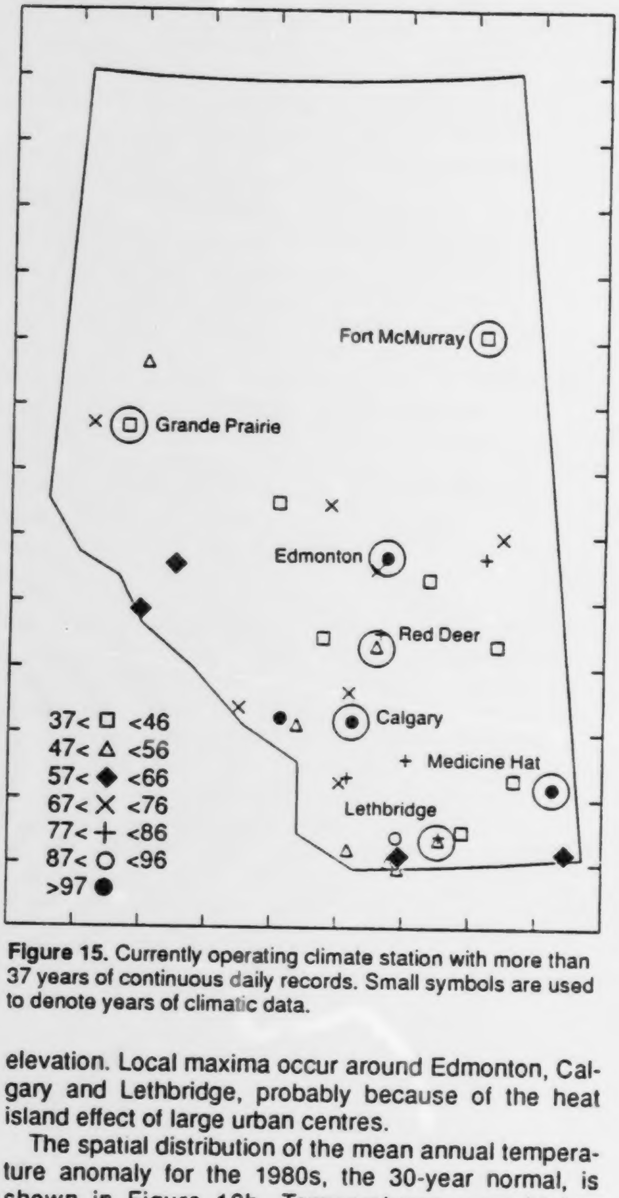


Figure 15. Currently operating climate station with more than 37 years of continuous daily records. Small symbols are used to denote years of climatic data.

Alberta's climate in the 1980s compared with the 1951-1980 normals

In the following comparisons of climate in the 1980s and the normal climate for 1951-1980, the 1980s are represented by only seven years of data (1980-1987), dictated by data availability at the time of analysis. Three parameters were examined: mean temperature; the annual average of the monthly temperature range, which was selected to represent variability; and total annual precipitation.

The results of the comparisons are shown in a series of three figures. Figure 18 shows the mean normal temperature pattern, the pattern of mean temperature anomaly (departure from the normal) for the 1980s, and the significance level for the differences in temperature. In Figure 18a, the pattern of mean temperatures for the normal period (1951-1980) is plotted. As expected, it illustrates a warmer climate in the south (about 5°C) and a colder climate in the north (approximately 0°C). Along the foothills, however, the surface temperature is lower because of the higher elevation. Local maxima occur around Edmonton, Calgary and Lethbridge, probably because of the heat island effect of large urban centres.

The spatial distribution of the mean annual temperature anomaly for the 1980s, the 30-year normal, is shown in Figure 18b. Temperatures were higher everywhere in Alberta during this period when compared with those of the normal period. The mean annual temperature anomaly varies from 0.2 to 1.4°C. The pattern reflects a slightly greater warming trend in the northern parts of the province, which may be a result of extrapolation in data-deficient areas. Along the foothills and around Coronation (in the southeastern part of Alberta), the mean annual temperature for the 1980s is less than 1°C warmer than the 30-year normal. Elsewhere in Alberta, the mean annual temperature is warmer than that for the normal period by more than 1°C. The average increase in temperature is about 0.5°C per decade for the province.

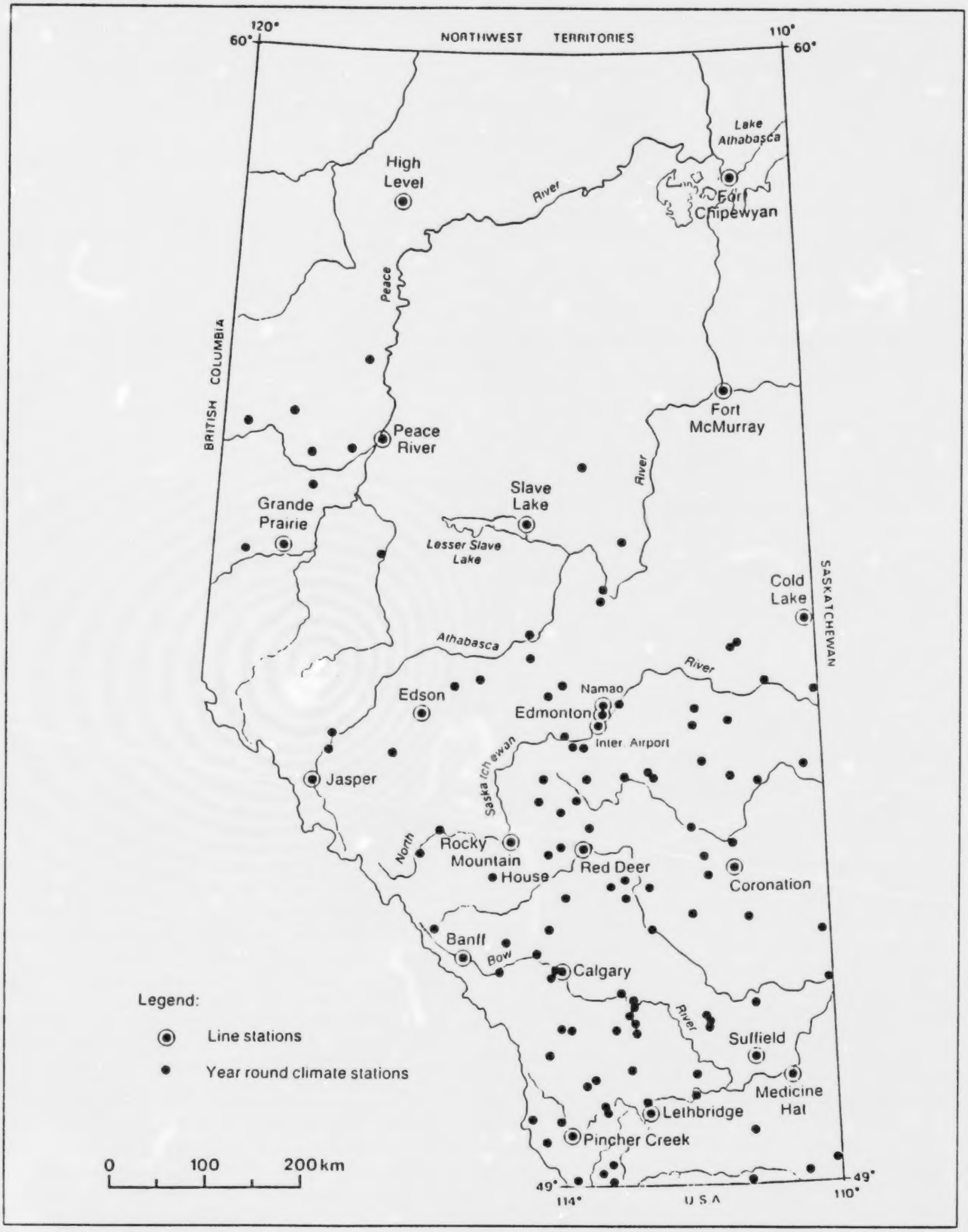

120°
60°
NORTHWEST TERRITORIES
110°
60°
Lake Athabasca
High Level
River
Fort Chipewyan
Peace
BRITISH COLUMBIA
Peace River
Fort McMurray
River
Grande Prairie
Slave Lake
Lesser Slave Lake
SASKATCHEWAN
Cold Lake
Athabasca
River
Edson
Namao
Edmonton
Inter. Airport
Jasper
Saskatchewan
North
Rocky Mountain House
Red Deer
Coronation
Banff
Bow
Calgary
River
Legend:
Line stations
Year round climate stations
Suffield
Medicine Hat
Lethbridge
Pincher Creek
0
100
200 km
49°
114°
U.S.A.
49°
110°

Figure 16. Available AES climate stations.

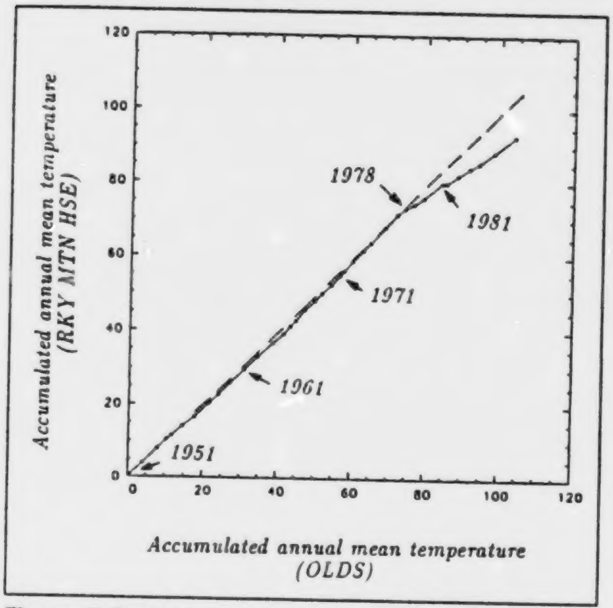


Figure 17. Double-mass curve of annual mean temperature at Rocky Mountain House and Olds.

Figure 18c shows the spatial distribution of the probability that the increase in mean annual temperature during the 1980s is due to chance. (In simple terms, a 5% significance level means that the probability of the difference between the samples being due to chance is 0.05.) The probabilities were computed using the Mann-Whitney test on the annual mean temperature data for the 30-year normal period and the 1981-1987 period. A value of 0.10 represents a significant difference at the 10% level. The results suggest that the increase in annual temperature during the 1980s is statistically significant at the 10% level in most parts of Alberta. Along the foothills and in the Coronation region, the temperature increase is not statistically significant.

Climate variability is represented by the annual mean of the monthly temperature range. This is defined as the annual average of the difference between the maximum and minimum temperatures for a particular month. Thus, a large value indicates a higher temperature fluctuation. Hereafter, this will be referred to as the "temperature range", for simplicity. Figure 19a shows the spatial distribution of the normal temperature range for Alberta. The 30-year normal temperature range varies from 31 to 36°C. The local maxima and minima illustrate local influences on warming.

Figure 19b shows the pattern of the temperature range anomaly for the 1980s compared to the normal period. Along a belt extending from Lethbridge to Coronation in southeastern Alberta, the temperature range in the 1980s is more extensive than that during the normal period. The average temperature range is smaller for the rest of Alberta. The relative increase or decrease in temperature range is rather small (less than 10%). Figure 19c illustrates the spatial distribution of probability that the difference in average temperature range in the 1980s is due to chance. Some of the increases and decreases are statistically significant at the 10% level.

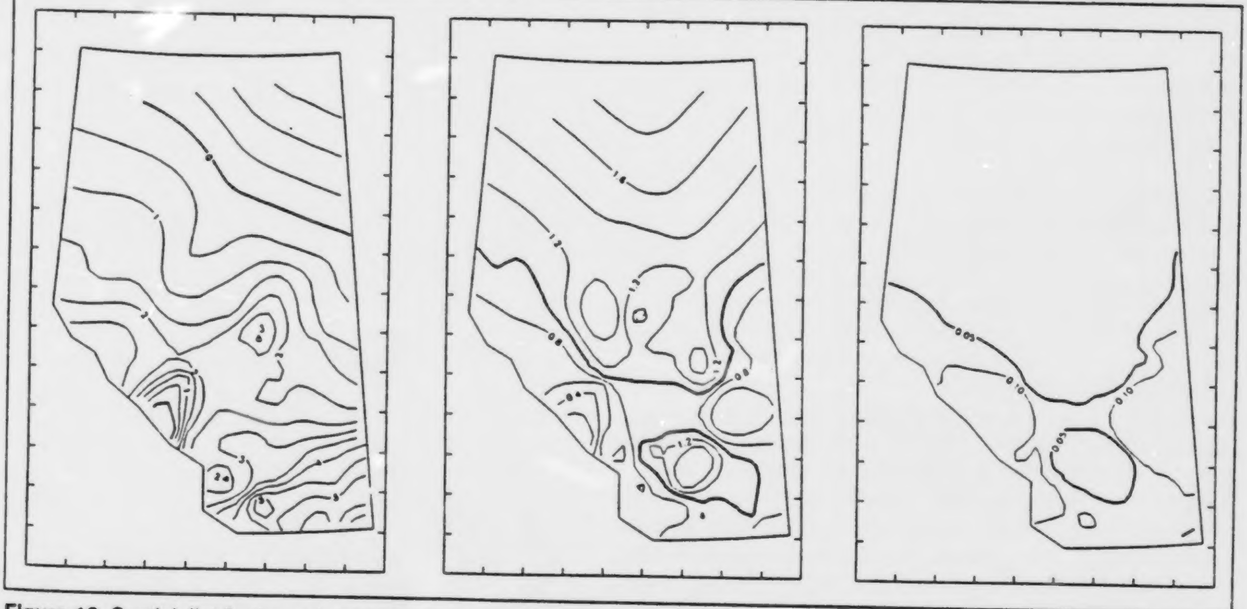


Figure 18. Spatial distributions of: (a) 1951-1980 normal annual temperature, with 0.5°C contour intervals, at Alberta; (b) anomaly of mean annual temperature, with 0.2°C contour intervals from the normal for the period 1981-1987 (c) probability that the difference between 1980's and the normal is due to chance (p-value from Mann-Whitney tests). Ticks on the axes represent 100 km.

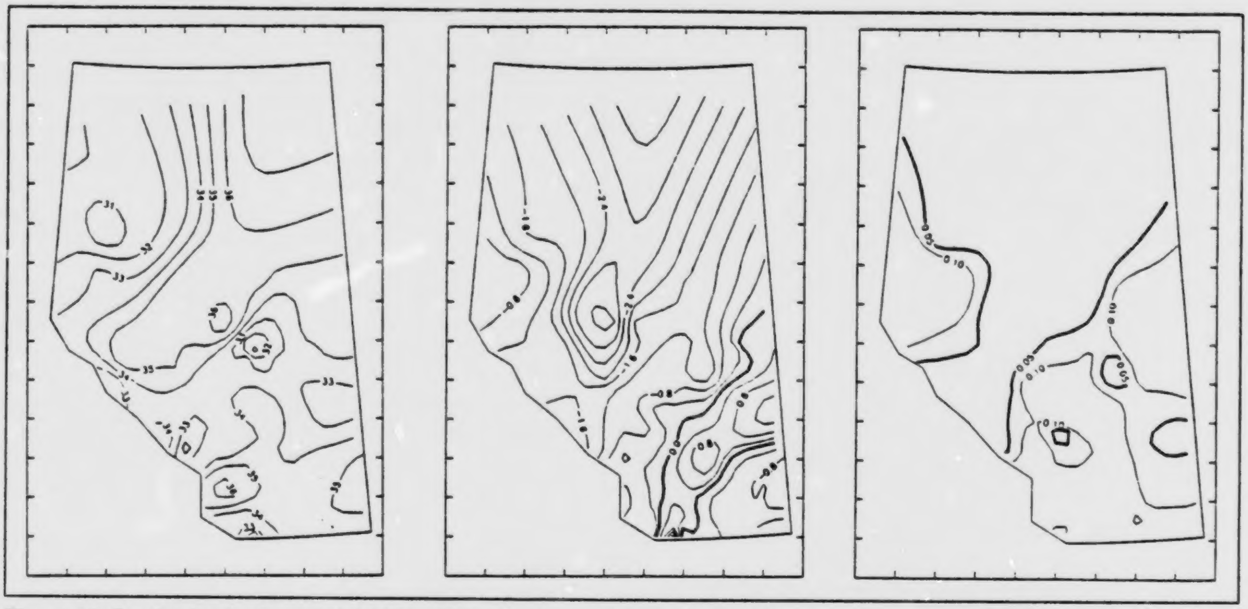


Figure 19. Spatial distributions of: (a) 1951-1980 normal annual mean of monthly temperature range, with 1°C contour intervals, at Alberta; (b) anomaly of mean annual temperature range, with 0.4°C contour intervals, from the normal for the period 1981-1987; (c) probability that the difference between 1980's and the normal is due to chance (p-value from Mann-Whitney tests). Ticks on the axes represent 100 km.

The pattern of the 30-year normal for total annual precipitation is shown in Figure 20a. Total annual precipitation is high along the foothills. This supports the general concept that more precipitation occurs at higher elevations (Hill et. al. 1981; Storr and Ferguson 1972). The southeastern corner of Alberta is the driest in the province. In Alberta, the normal total annual precipitation varies between 330 and 720 mm.

The deviation in total mean annual precipitation during the 1981-1987 period compared to that of the 30-year normal is given in Figure 20b. A decrease in precipitation of more than 40 mm/yr is seen along the foothills and in east-central Alberta. In an elongated region from Edson to Medicine Hat, a small increase in the mean total annual precipitation during the 1981-1987 period was seen. In general, the change in total annual precipitation is relatively small and not statistically significant (Figure 20c).

Long term trends

In the previous analyses, it was shown that there were differences between the 1980s and the normal period for certain climate parameters. It is of interest to note the kinds of long-term trends that exist in the climatological records of Alberta. Trends for mean annual temperature, mean annual temperature range, and total precipitation were determined for each station using linear regression analysis, and the spatial distribution of such trends are examined.

Data from the stations shown in Figure 15 were used. There were some trend variations because data has been collected for different lengths of time for all stations. When analyses were repeated for records involving the same period of time for all stations, however, no significant qualitative differences in distribution patterns were observed, although the actual values of the trends obtained were different. Figure 21 shows the spatial distribution of mean temperature trends determined from all available data. The locations of the maxima and minima are similar to those in Figure 22 when records involving the same length of time were used throughout. For this part of the study, the results from all available data were used. Subsequent analysis will involve separating the available time sequences into subsamples of equal length. Figure 21 shows that, excluding a few pockets of very small negative values, warming trends of up to 4°C per century exist in Alberta (the extrapolated values for northern Alberta were not considered). Averaging the temperature trends obtained from the stations, a general warming of 1.3°C per century was obtained. The causes for the individual pockets in the pattern are undetermined. They may be caused by local influences, data noise, or simply the uneven distribution of monitoring stations. A "cleaned" data set should be used in subsequent analyses for better definition of spatial patterns.

The pattern of temperature range trends in Alberta is given in Figure 23. The trends are negative everywhere in Alberta, except in the southeastern part of the province around Coronation, the Canada-U.S.A. border, and southeast of Calgary. These results suggest that temperature variability is decreasing in most

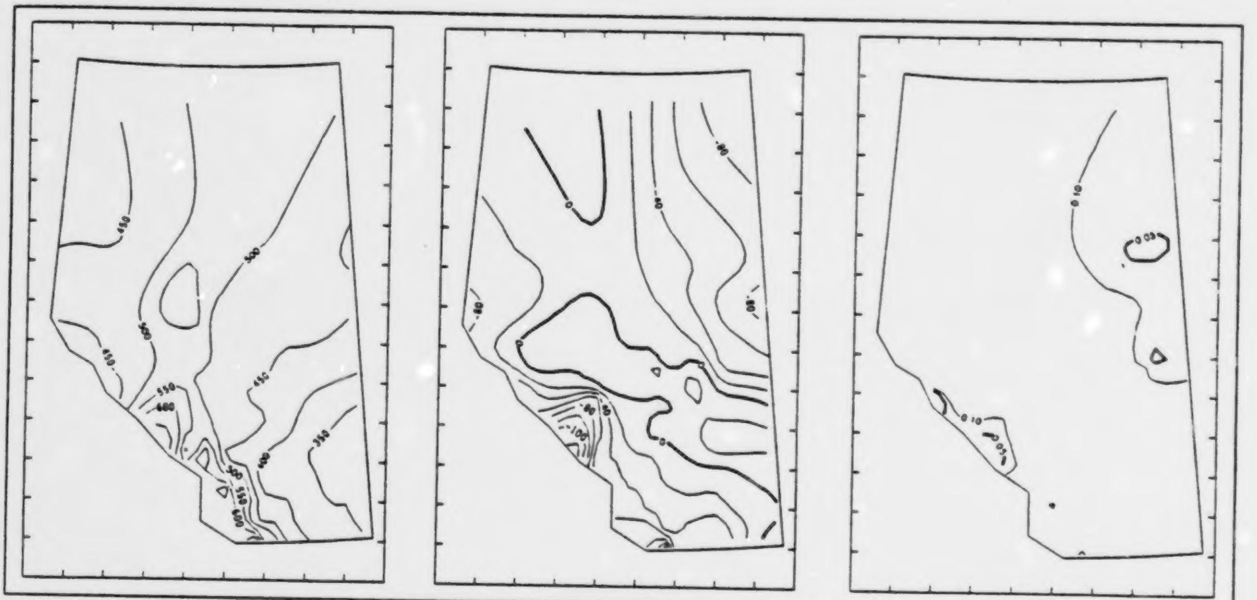


Figure 20. Spatial distributions of: (a) 1951-1980 normal annual total precipitation, with 100 mm yr^{-1} contour intervals, at Alberta; (b) anomaly of mean annual precipitation, with 20 mm yr^{-1} contour intervals, from the normal for the period 1981-1987; (c) probability that the difference between 1980's and the normal is due to chance (p-value from Mann-Whitney tests). Ticks on the axes represent 100 km.

parts of Alberta. The average of the temperature range trends for all the stations is -3.43°C per century. There is a certain degree of negative correlation between the temperature range pattern depicted in Figure 23 and that of mean temperature shown in Figure 21. Particularly noteworthy is the local maximum in southeastern Alberta shown in Figure 23, and the local minimum for the same region shown in Figure 21.

Figure 24 shows the total annual precipitation trend, derived from all available records from the 34 stations used in the study. The total annual precipitation is increasing in the east-central part of the province. Less precipitation is falling along the foothills and in southeastern Alberta. The average of the total annual precipitation trend for all Alberta is 10 mm per century. Unlike the situations with mean annual temperature and temperature range, there is no predominant areal extent of decrease or increase in total annual precipitation in Alberta.

Appendix A lists the details of the trends obtained from the individual stations for annual temperature, mean annual temperature range, and total annual precipitation.

It has been suggested that greenhouse warming is greater in the winter at high latitudes (Mitchell 1983; Manabe and Stouffer 1980). Long-term trends for the winter season (December through February) were examined. Linear regression analyses were performed for the winter seasonal mean temperature, temperature range, and total precipitation. The results for mean temperature are summarized in Figure 25. The pattern for the seasonal mean temperature trend resembles that for annual mean temperature, but with values about 2°C per century higher at the local maxima and minima. There are three small pockets of negative values, probably a result of local effects. Elsewhere the trends are positive. The winter seasonal warming trend average for all the stations is 2.17°C per century, almost double the value for the annual mean temperature. It would be interesting to reevaluate the magnitude of the winter trends after some adjustment for bias caused by the urban warming effect.

Figure 26 shows the spatial distribution of the trend in the seasonal average temperature range. This is again similar to the annual pattern. The values at the local maxima and minima are smaller by about 2°C per century. Averaged over all the stations, the seasonal temperature range trend is -4.88°C per century. The reduction in temperature variability is greater in the winter season than for the entire year.

The spatial distribution of the trend in total winter seasonal precipitation is given in Figure 27. Unlike the previous cases, the pattern is different from that of the total annual precipitation. Nevertheless, the two patterns both show a decrease in precipitation in the foothills and Medicine Hat area of southeastern Alberta. Averaged overall the stations, the total winter seasonal precipitation trend is -9.8 mm per century.

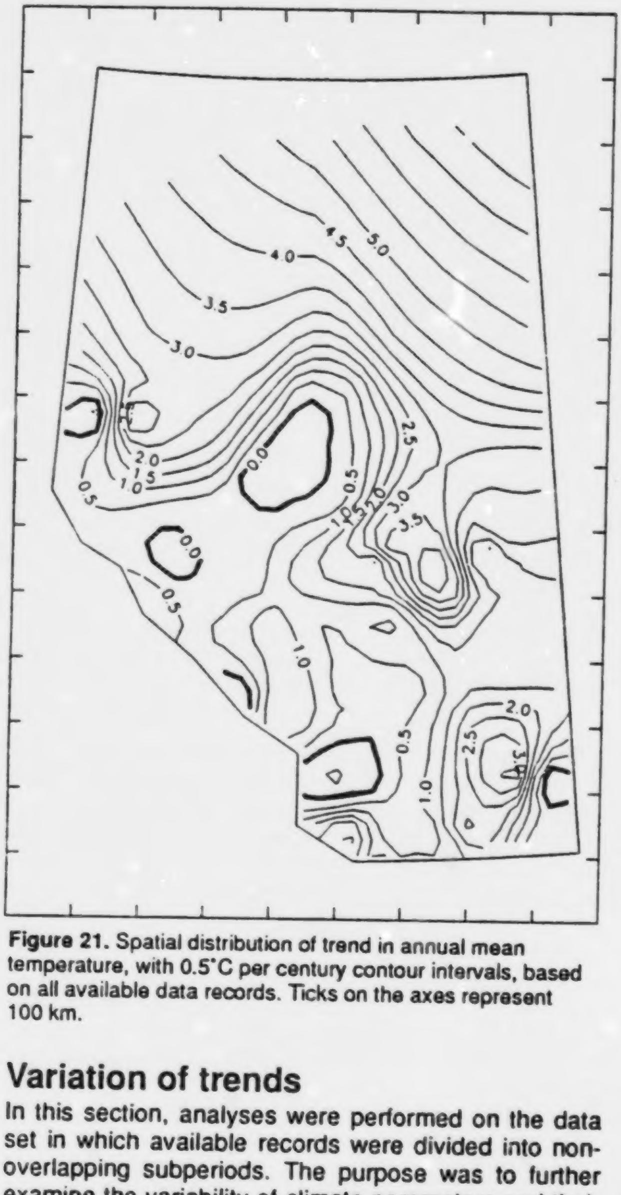


Figure 21. Spatial distribution of trend in annual mean temperature, with 0.5°C per century contour intervals, based on all available data records. Ticks on the axes represent 100 km.

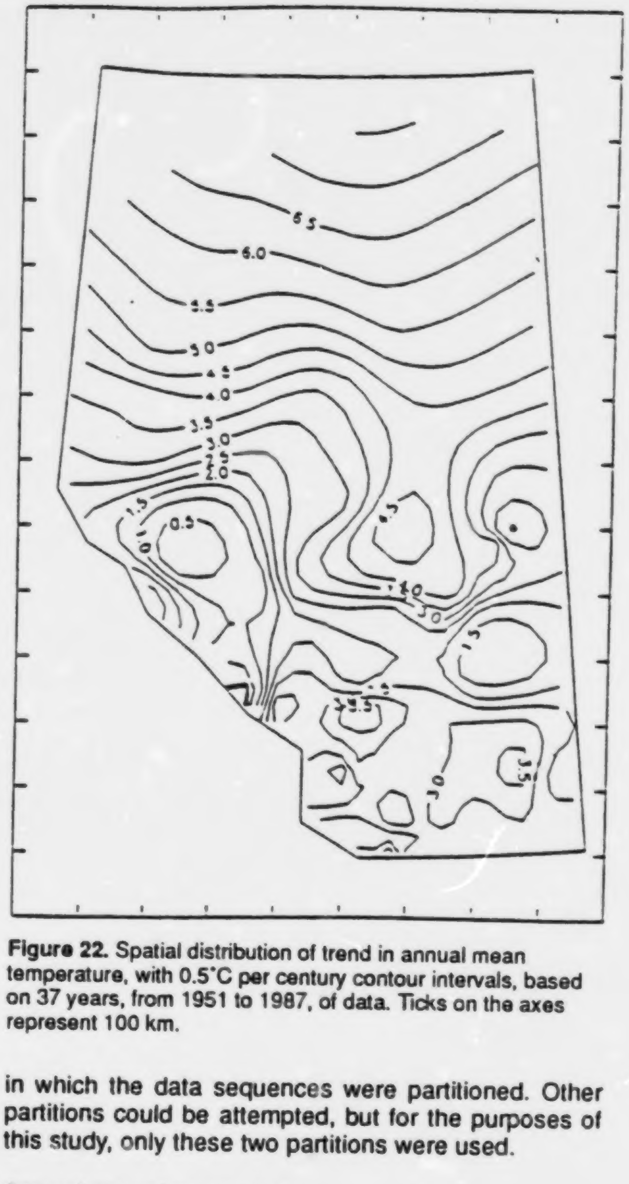


Figure 22. Spatial distribution of trend in annual mean temperature, with 0.5°C per century contour intervals, based on 37 years, from 1951 to 1987, of data. Ticks on the axes represent 100 km.

Variation of trends

In this section, analyses were performed on the data set in which available records were divided into nonoverlapping subperiods. The purpose was to further examine the variability of climate parameters and their trends. For each station, the time sequences of climate parameters were first divided into seven subperiods consisting of 1981-1987 and the following 10-year periods: 1921-1930, 1931-1940, 1941-1950, 1951-1960, 1961-1970, and 1971-1980. The data for all the stations were analyzed for each of the seven subperiods. This set of subdivided data will be referred to as partition I. For comparison, a second set of subdivided data was obtained by regrouping the time sequences into seven 10-year subperiods consisting of 1918-1927, 1928-1937, 1938-1947, 1948-1957, 1958-1967, 1968-1977, and 1978-1987. This will be referred to as partition II. The purpose of the second partition is to examine the sensitivity of the results to the method in which the data sequences were partitioned. Other partitions could be attempted, but for the purposes of this study, only these two partitions were used.

Annual mean temperature

Figure 28 shows the spatial distributions of the mean annual temperature and trend for partition I. The patterns for mean temperature are similar to those for the different subperiods. There is a general north-south temperature gradient and the heat island effect has become more pronounced for large urban centres such as Edmonton, Calgary, and Lethbridge in recent years.

The spatial distribution of the temperature trend varies greatly for the different subperiods. The 1920s saw increasing temperatures in Alberta, with the exception of several small areas of local minima in southern Alberta. There was also a slight cooling in the southeastern corner of the province. The mag-

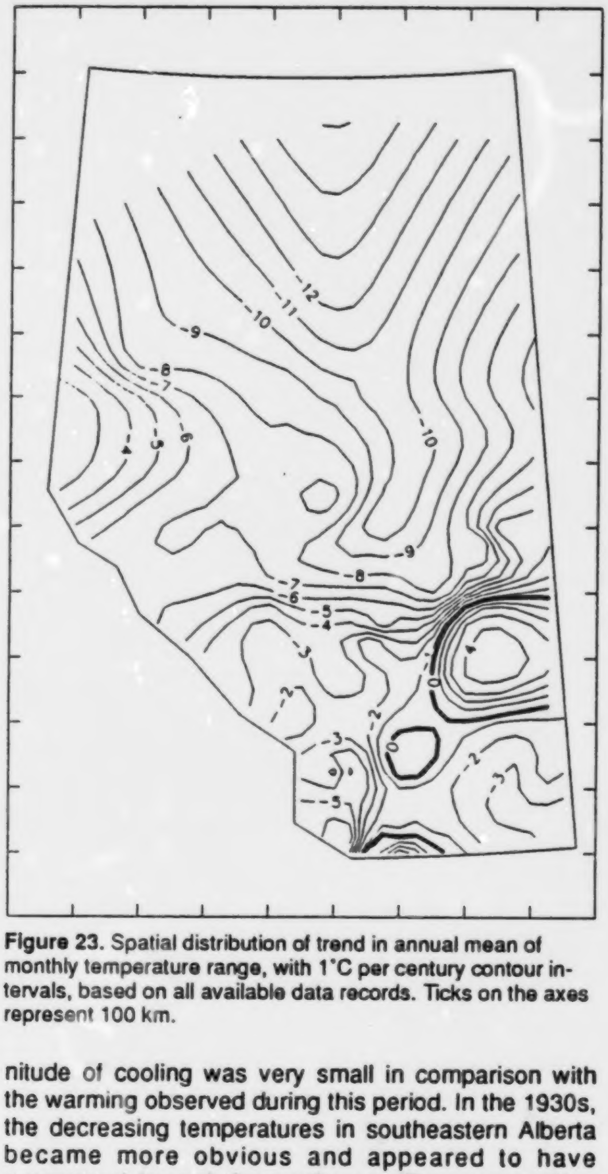


Figure 23. Spatial distribution of trend in annual mean of monthly temperature range, with 1°C per century contour intervals, based on all available data records. Ticks on the axes represent 100 km.

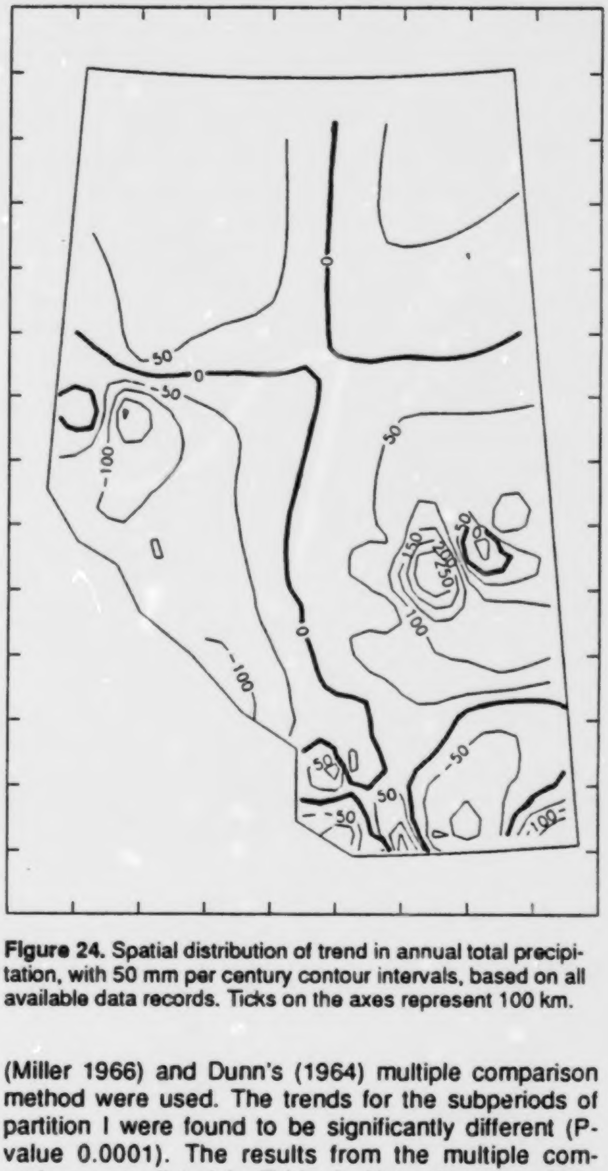


Figure 24. Spatial distribution of trend in annual total precipitation, with 50 mm per century contour intervals, based on all available data records. Ticks on the axes represent 100 km.

nitude of cooling was very small in comparison with the warming observed during this period. In the 1930s, the decreasing temperatures in southeastern Alberta became more obvious and appeared to have progressed toward the northwest. There was still a general warming trend in the province during this period. Warming during the 1950s ranged from 0.5 to 3.0°C per decade. In the 1960s the province underwent another period of cooling, the temperature change ranging from -0.5 to -2.5°C per decade, followed again by a decade of warming in the 1970s. Note that there was an increase in mean temperature during the 1970s for most of Alberta, but little or no increase in the mountain areas. Warming in the 1980s was in the range of 2.0 to 3.5°C per decade. This contains the greatest warming rate observed for Alberta since the beginning of records.

Statistical tests were performed to determine the significance of the differences in trends for the various subperiods. The distribution-free Kruskal-Wallis test (Miller 1966) and Dunn's (1964) multiple comparison method were used. The trends for the subperiods of partition I were found to be significantly different (P-value 0.0001). The results from the multiple comparisons are listed in Table 9. Note that the 1980s stand out as the only subperiod that is significantly different from all others in the data sequence.

Table 9. Summary of results for comparing trends of annual mean temperature for partition I. An asterisk above the diagonal indicates significant difference for the periods compared at the 5% level based on Dunn's method.

	21-30	31-40	41-50	51 -60	61-70	71-80	81-87
21 - 30			*		*		*
31 - 40			*	*		*	*
41 - 50				*		*	*
51 - 60					*		*
61 - 70						*	*
71 - 80							*

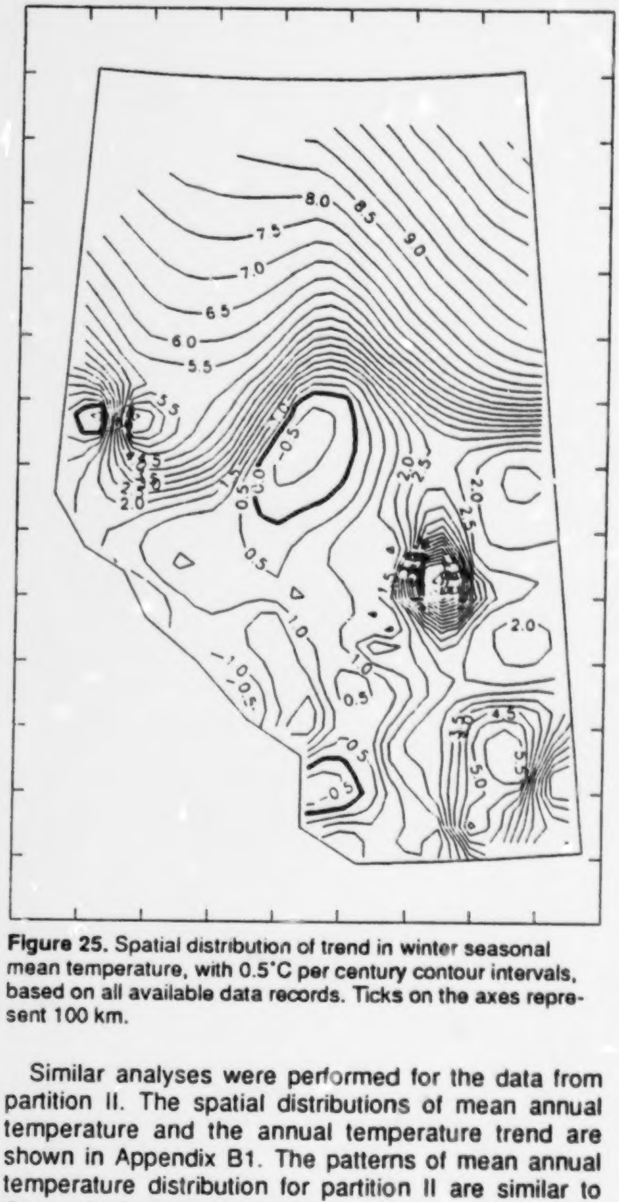


Figure 25. Spatial distribution of trend in winter seasonal mean temperature, with 0.5°C per century contour intervals, based on all available data records. Ticks on the axes represent 100 km.

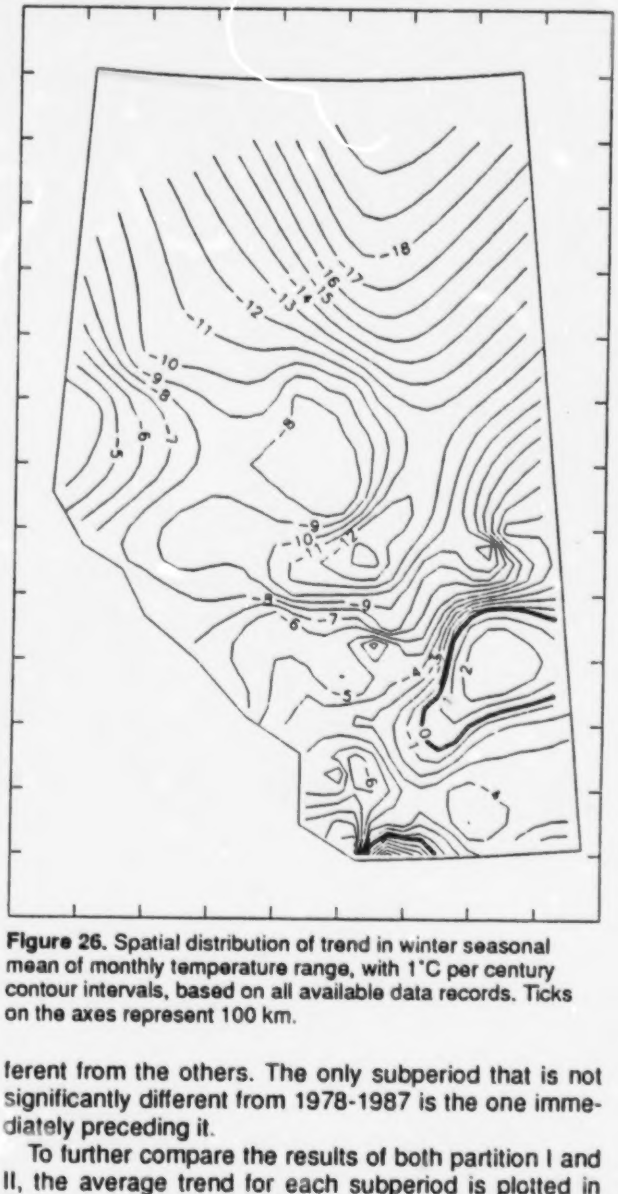


Figure 26. Spatial distribution of trend in winter seasonal mean of monthly temperature range, with 1°C per century contour intervals, based on all available data records. Ticks on the axes represent 100 km.

Similar analyses were performed for the data from partition II. The spatial distributions of mean annual temperature and the annual temperature trend are shown in Appendix B1. The patterns of mean annual temperature distribution for partition II are similar to those obtained from partition I. It appears that mean annual temperature patterns are not particularly sensitive to small shifts in the definition of the subperiods. The trend patterns, however, are quite different from those obtained for partition I. For example, there was more cooling during the 1918-1927 and 1928-1937 subperiods than the corresponding 1920s and 1930s decades. This indicates that estimates of the trends in the subperiods are sensitive to minor shifts in the definitions involved.

The overall comparison of temperature trends in partition II indicates that the there are significant differences in the subperiods (P-value 0.0001). The multiple comparison results are listed in Table 10. The 1978-1987 period still stands out as the one most different from the others. The only subperiod that is not significantly different from 1978-1987 is the one immediately preceding it.

To further compare the results of both partition I and II, the average trend for each subperiod is plotted in Figure 29. The values are plotted on the central point of each period. The overall trend averages are 1.2°C per century for partition I and 0.5°C for partition II.

Table10. Summary of results for comparing trends of annual mean temperature for partition II. An asterisk above the diagonal indicates significant difference for the periods compared at the 5% level based on Dunn's method.

	18-27	28-37	38-47	48-57	58-67	68-77	78-87
18 - 27						*	*
28 - 37				*		*	*
38 - 47				*		*	*
48 - 57					*		*
58 - 67						*	*
68 - 77							

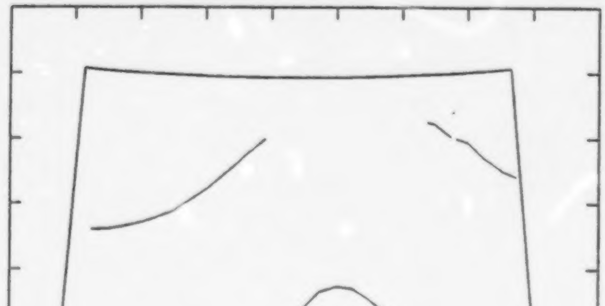


Figure 27. Spatial distribution of trend in winter seasonal precipitation, with 50 mm per century contour intervals, based on all available data records. Ticks on the axes represent 100 km.

There are only minor differences between the two partitions in trend fluctuations. Note the increasing trend (this is in fact, an increasing trend in temperature trend) and the peak positions in the last subperiod (Figure 29), indicating the largest warming trend in the 1980s.

Annual mean of monthly temperature range

The same analyses were performed for the mean annual temperature range. The spatial patterns of the mean temperature range and its trend for the subperiods of partition I are shown in Figure 30. As with mean temperature, there is much less variability in the spatial distribution of the mean values than in the trends. There are also some common features in the patterns such as the ridge of high values extending northeast from central Alberta, and various pockets of local maxima and minima.

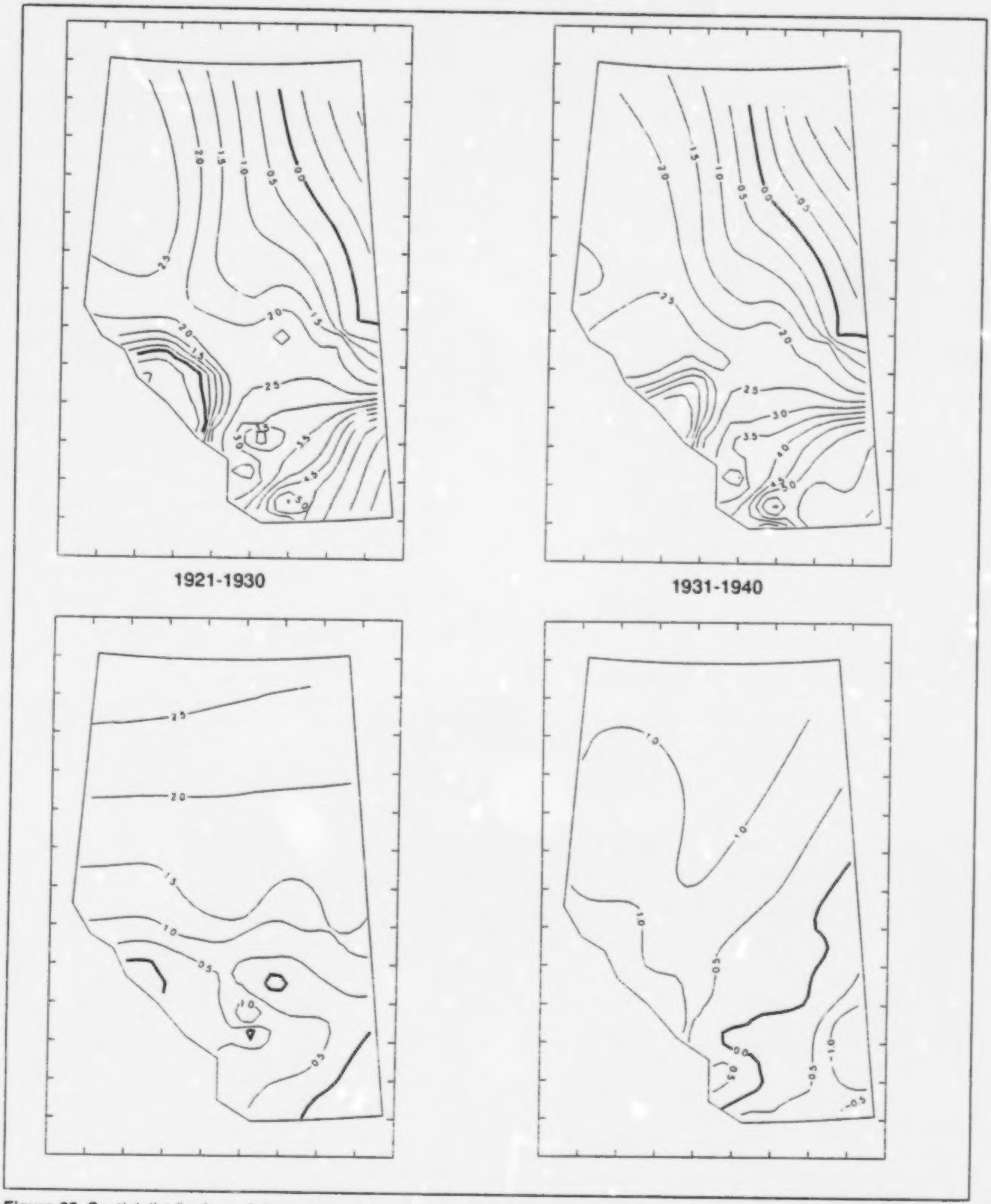
The spatial distribution of the trend, however, varies significantly from subperiod to subperiod. In the 1920s, the temperature range trend was characterized by a centre of negative values in south-central Alberta. The decreasing trend in this area was estimated at approximately -3.0°C per decade. There were both increasing and decreasing trends in Alberta in the 1930s, and the general pattern shows significant negative trends in the south with some positive trends in the central and eastern parts of the province. Averaged over the whole province, there was a decreasing temperature range trend in this subperiod. The temperature range trends decreased further in the 1940s. Excluding a strip along the foothills, the trend was negative for Alberta. The distribution of the temperature range trend in the 1950s was similar to that of the 1940s, but the positive trend area along the foothills was reduced. The trend continued to decrease during the 1960s except for local maxima of positive values in the mountains and the southeastern part of the province. In the 1970s more areas of increasing temperature trends existed in the province. In addition, the maximum value of an increasing trend was larger than that for a decreasing trend for the first time during the entire study period. Finally, the 1980s saw both increasing and decreasing temperature range trends throughout Alberta. The temperature range increased in the southwest part of the province and decreased in the northeast. The change in sign for trend occurs over a line roughly parallel to the mountains. Averaged over the entire province, the temperature range trend was slightly positive for this subperiod.

The results of statistical tests in Table 11, show that the temperature range trends for the subperiods are only marginally different (P-value of 0.1055). The details revealed by the multiple comparison results show that significant differences existed for only four comparisons of the subperiods: the 1980s with either the 1950s or the 1960s, and the 1970s with either the 1950s or the 1960s.

Similar temperature range analyses were performed for the subperiods of partition II. The results are shown in Appendix B2 and Table 12, and as before, indicate that the pattern for the mean values is more resistant to shifts in the definition of the subperiods than for the trends. Many more significant differences are seen in Table 12 than Table 11 with only a three-

Table 11. Summary of results for comparing trends of annual mean temperature range for partition I. An asterisk above the diagonal indicates significant difference for the periods compared at the 5% level based on Dunn's method.

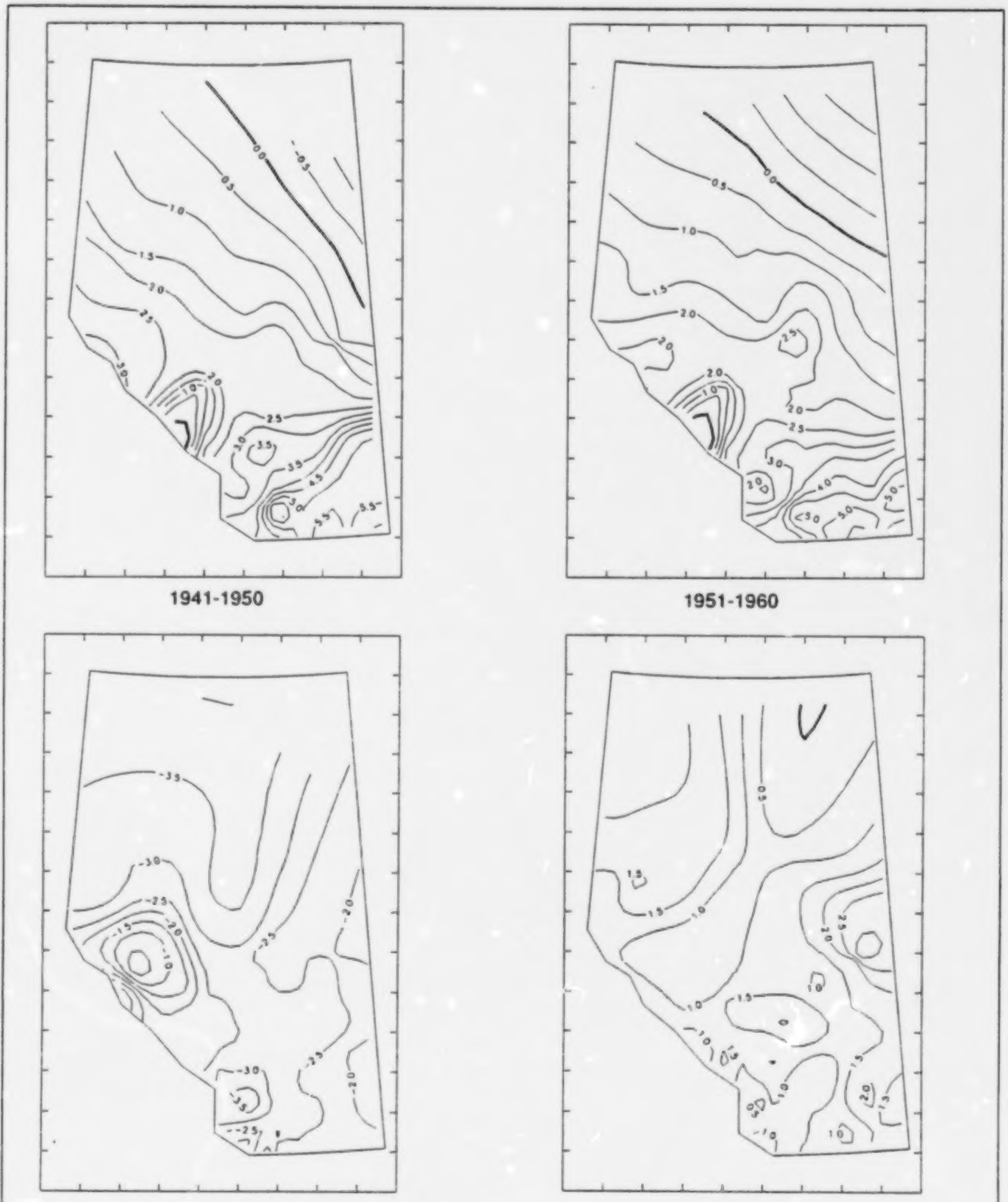
	21-30	31-40	41-50	51-60	61-70	71-80	81-87
21 - 30							
31 - 40							
41 - 50							
51 - 60						*	*
61 - 70						*	*
71 - 80							



1921-1930

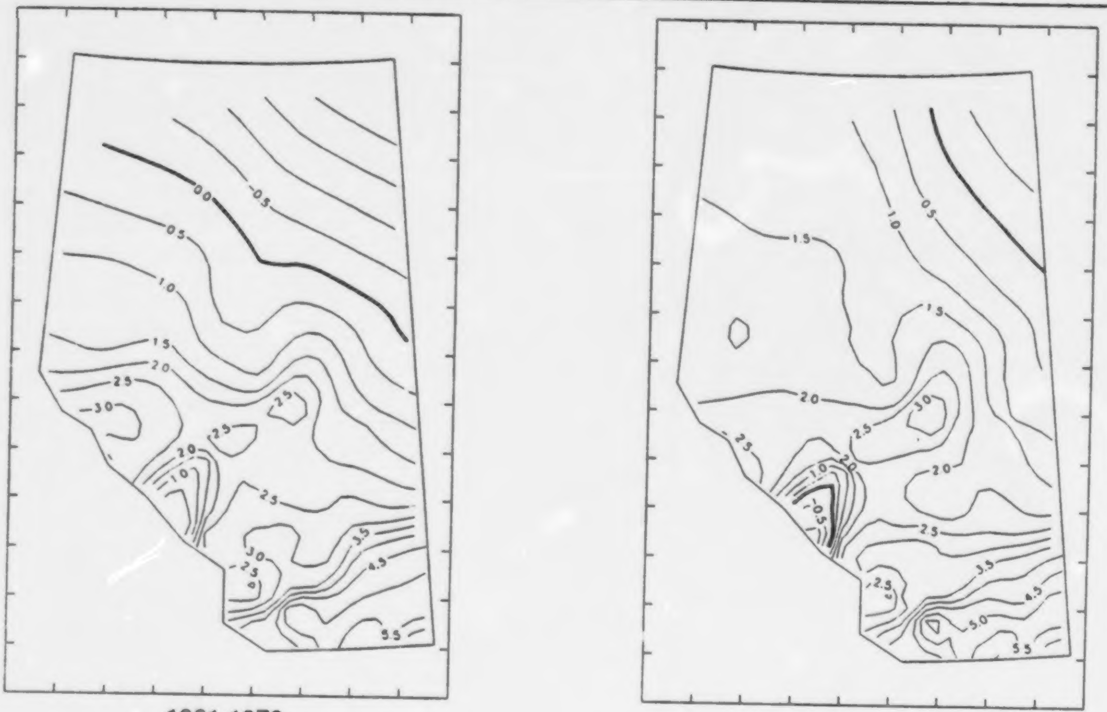
1931-1940

Figure 28. Spatial distributions of decadal mean (top row) and trend (bottom row) of annual mean temperature for the 1920s to 1980s. Contour intervals for the mean and trend are 0.5°C and 0.5°C (10 yr)$^{-1}$ respectively. Ticks on the axes represent 100 km.



1941-1950
1951-1960

Figure 28. (continued)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-0.5
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1961-1970

1971-1980

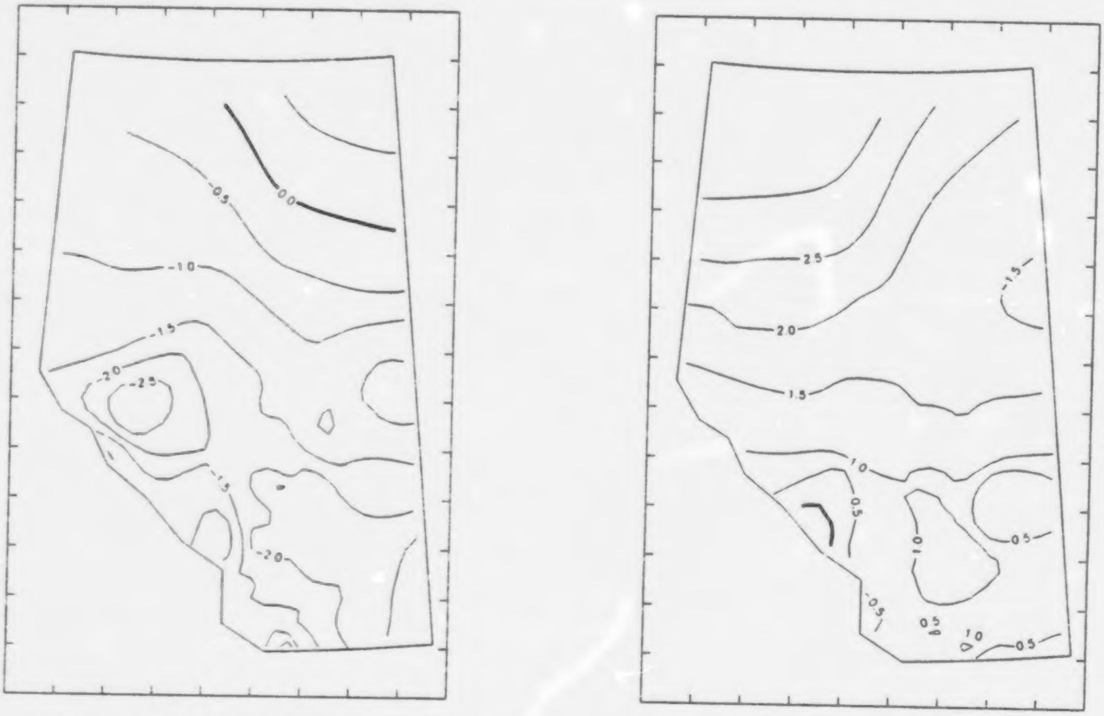
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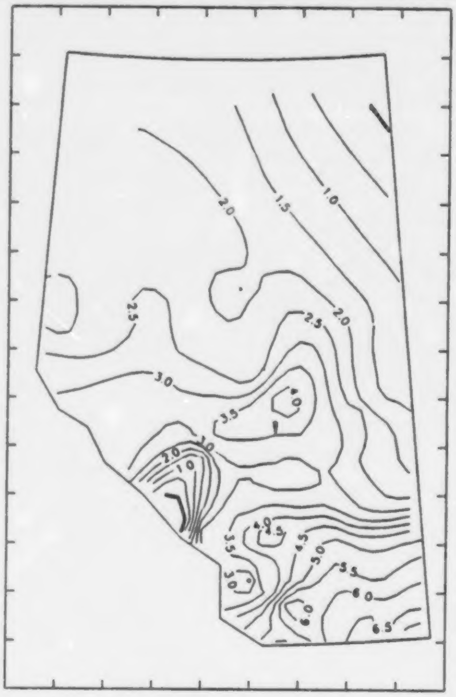
Figure 28. (continued)



1981-1987

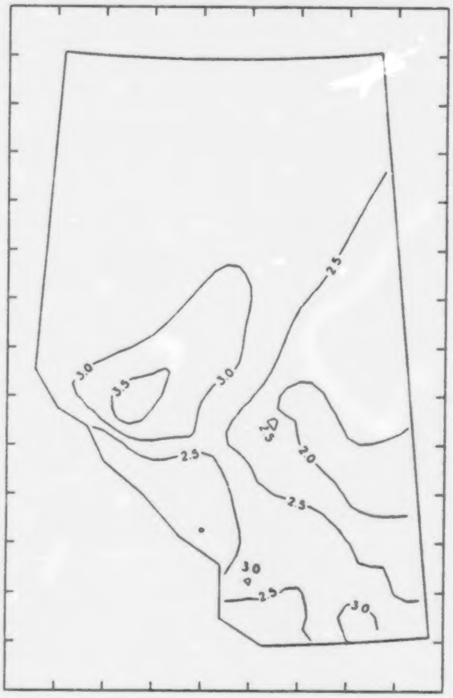


Figure 28. (continued)

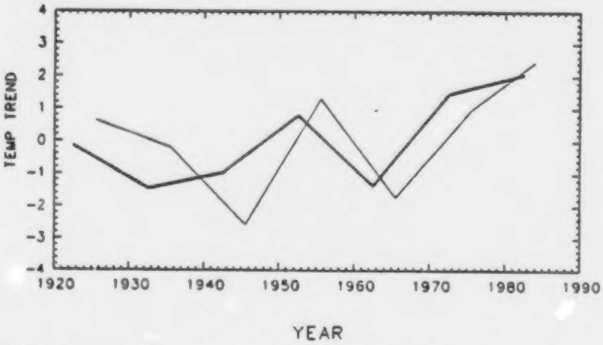


Figure 29. Alberta averaged annual mean temperature decadal trend for partition I (thin line) and partition II (thick line) in °C per decade.

year shift in subperiod definition between partition I and partition II.

The results of the data sequences from the two partitions are summarized in Figure 31. There is much less similarity between the two curves than for mean annual temperature. In fact, the two partitions show opposite temperature range trends in recent years, and the two curves in Figure 31 show different overall trends. The average values for temperature range trends in Alberta are -8.3°C per century for partition I and -3.7°C per century for partition II. From this part of the analysis, it appears that overall negative trends in temperature range are the only indication of significant change.

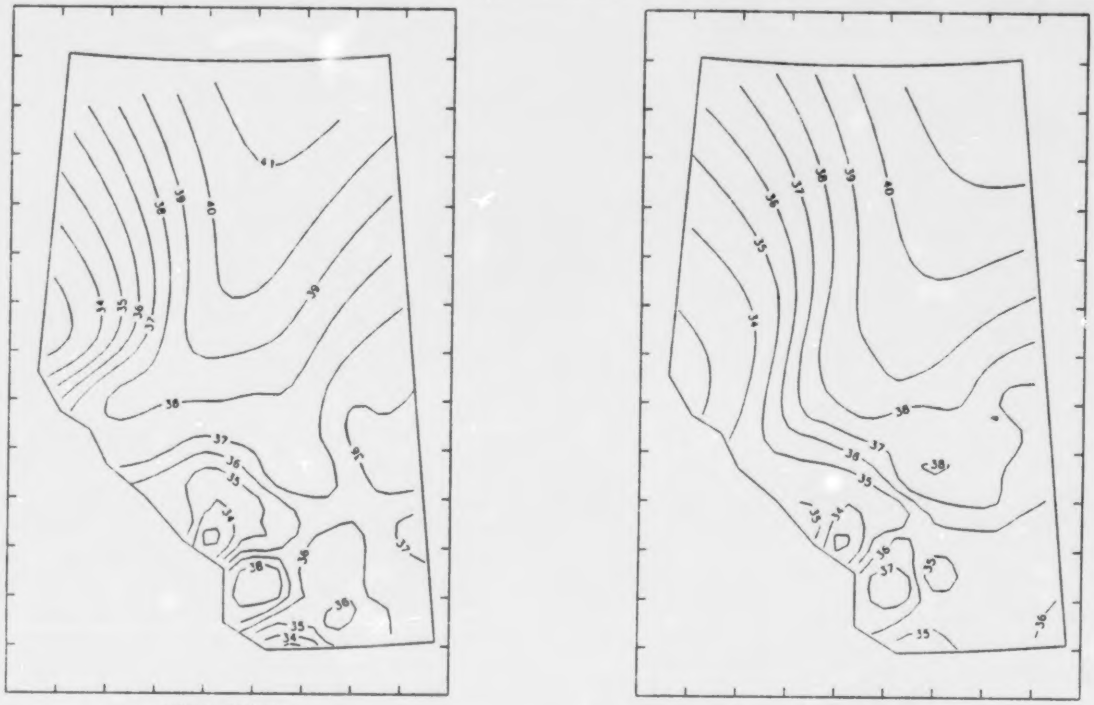
Total annual precipitation

Because no statistically significant difference was obtained for total precipitation when the 1980s were compared with the normal period (1951-1980), and there was large variability in precipitation trends for all of Alberta (Figure 24), the analysis of total precipitation using the partitioned data did not serve the same purpose as that done for temperature. Nevertheless, the same analyses were performed and results are included for the sake of completeness and for showing the type of variability one can expect from the precipitation field.

Figure 32 shows that total mean precipitation and trend distribution for each of the subperiods in parti-

Table 12. Summary of results for comparing trends of annual mean temperature range for partition II. An asterisk above the diagonal indicates significant difference for the periods compared at the 5% level based on Dunn's method.

	18-27	28-37	38-47	48-57	58-67	68-77	78-87
18 - 27		*	*	*	*	*	*
28 - 37			*	*		*	*
38 - 47							
48 - 57					*		
58 - 67						*	*
68 - 77							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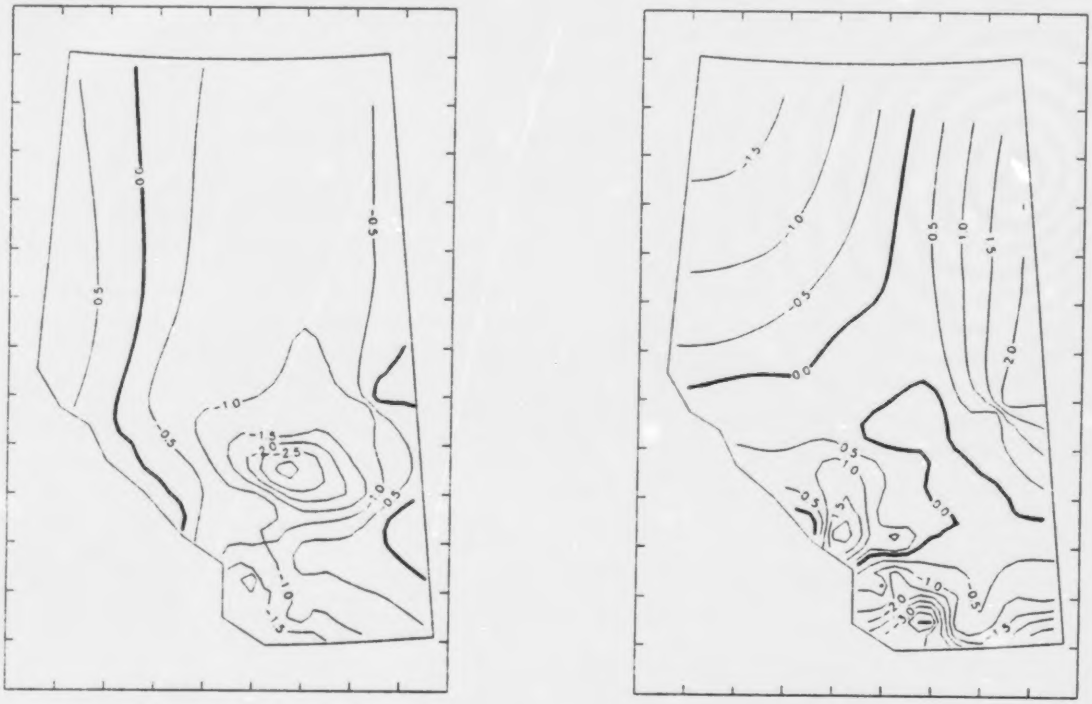
1921-1930

1931-1940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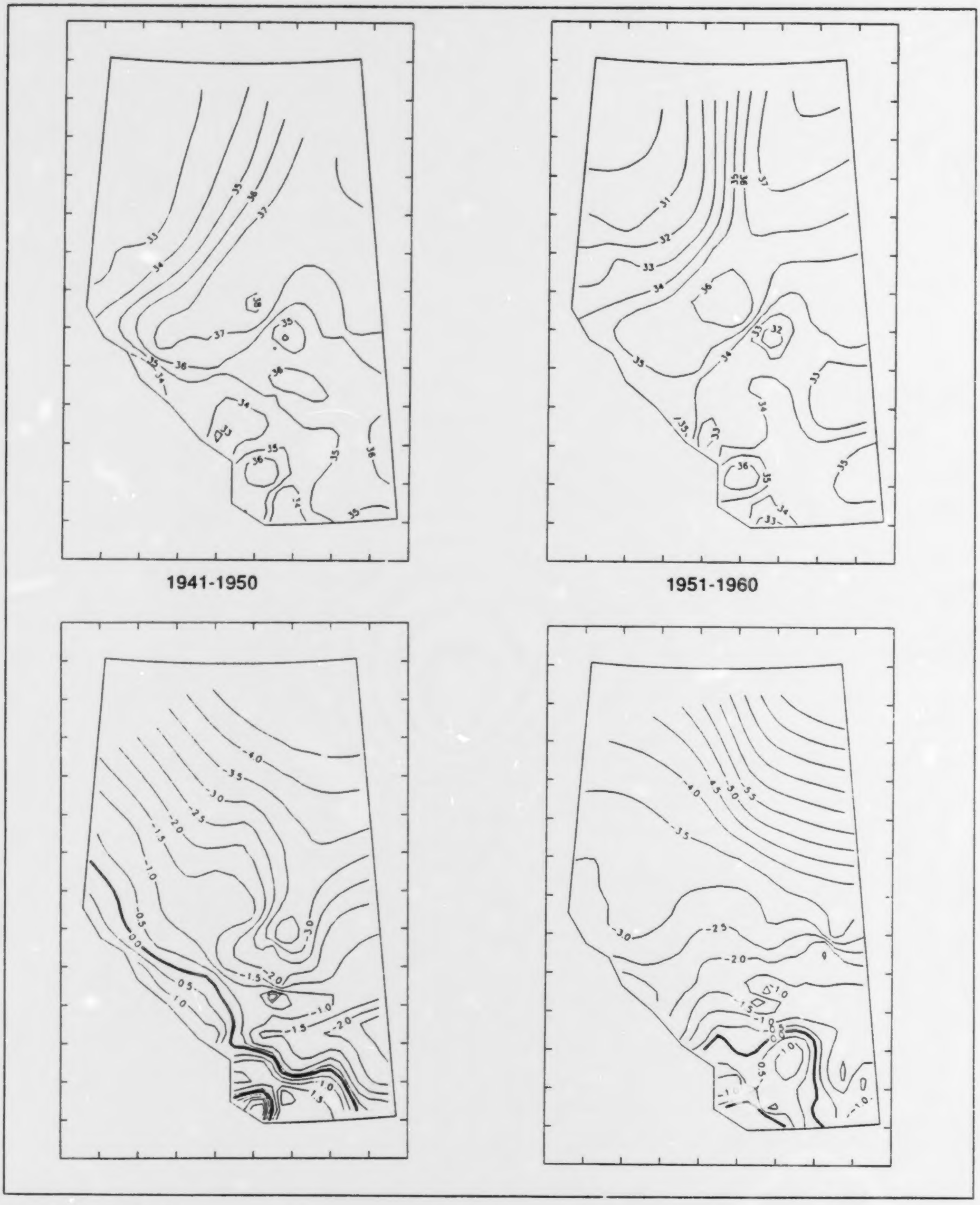
-3.0
-1.5

Figure 30. Spatial distributions of decadal mean (top row) and trend (bottom row) of annual mean of monthly temperature range for the 1920s to 1980s. Contour intervals for the mean and trend are 1°C and 0.5°C (10 yr)$^{-1}$ respectively. Ticks on the axes represent 100 km.



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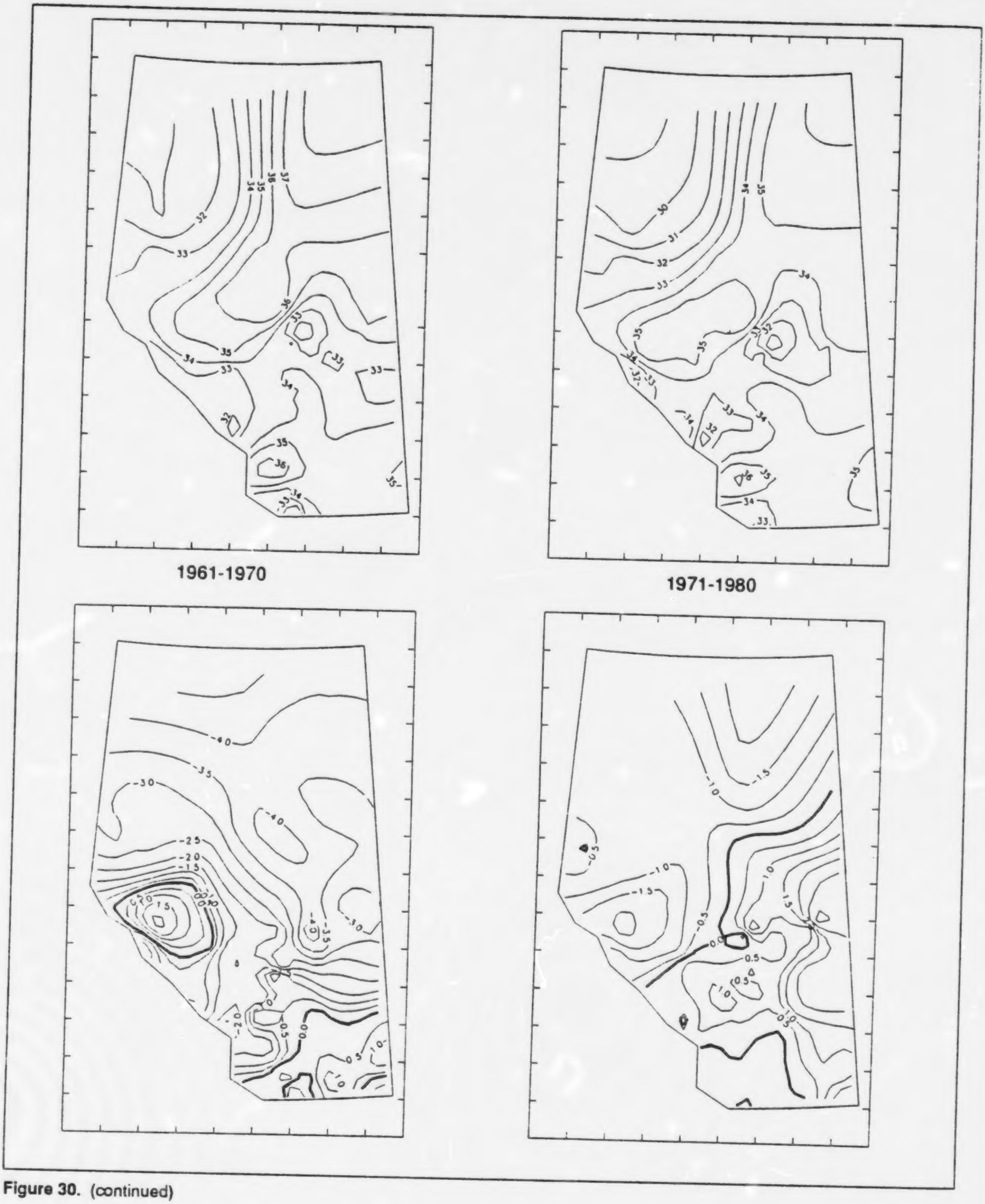
1941-1950

1951-1960

Figure 30. (continued)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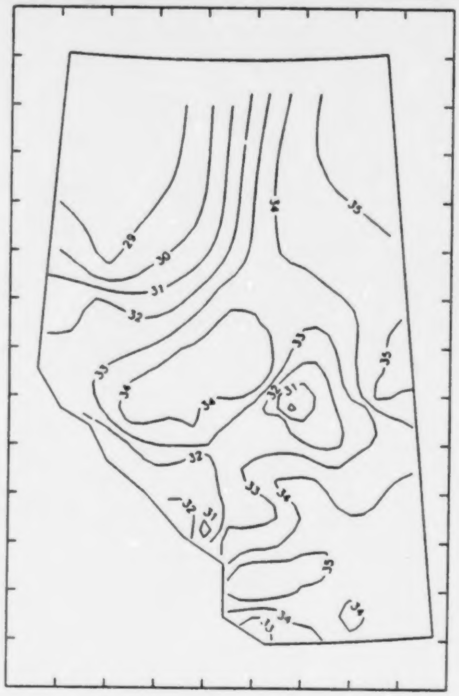
1961-1970

1971-1980

Figure 30. (continued)



1981-1987

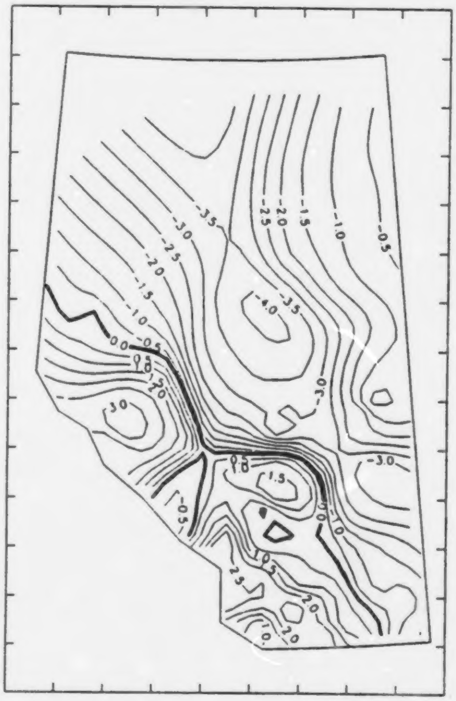


Figure 30. (continued)

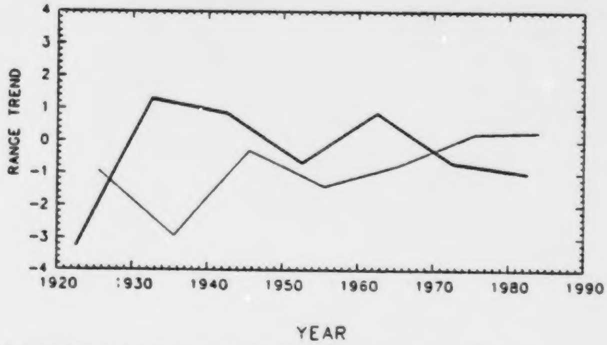


Figure 31. Alberta averaged annual mean temperature range decadal trend for partition I (thin line) and partition II (thick line) in °C per decade.

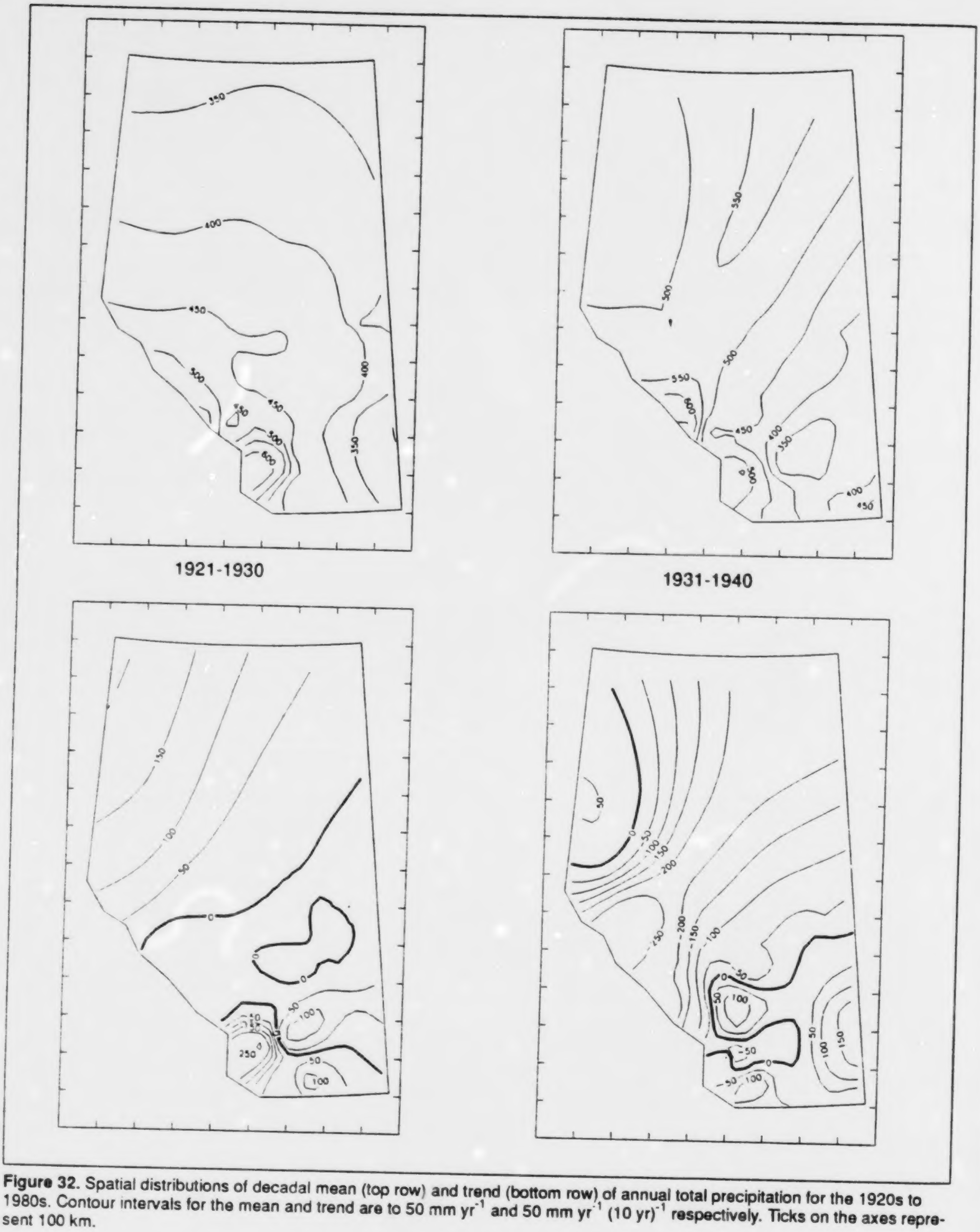
tion I. The same information is shown for partition II in Appendix B3. In general, there was large variability both in the mean total precipitation and its trend. In the distributions of total mean precipitation, one can still see the influence of orography along the foothills and the semi-aridity in the southeast. Variability was so large in the patterns of precipitation trends, however, that no consistent explanation can be given. The subperiod trends for Alberta are shown in Figure 33 for the two partitions. The average value is -19 mm per century for partition I and 47 mm per century for partition II, showing considerable sensitivity of the results to the manner in which subperiods are defined. In addition, Tables 13 and 14 show that the differences in precipitation trend changed significantly from partition I to partition II. This is probably a result of bias caused by extreme values in the data sequences. Some form of spatial or temporal data smoothing should be used to reveal the precipitation trends. Alternatively, robust regression methods could be used to reduce outlier effects.

Observations

From the above analysis, it is clear that the 1980s is a warmer than normal period for Alberta, and the rate of warming is probably the greatest it has ever been compared with periods of similar length in the historical record. In addition, the range in temperature has

Table 13. Summary of results for comparing trends of annual total precipitation for partition I. An asterisk above the diagonal indicates significant difference for the periods compared at the 5% level based on Dunn's method.

	21-30	31-40	41-50	51-60	61-70	71-80	81-87
21 - 30				*			
31 - 40				*			
41 - 50				*			
51 - 60					*	*	*
61 - 70							
71 - 80							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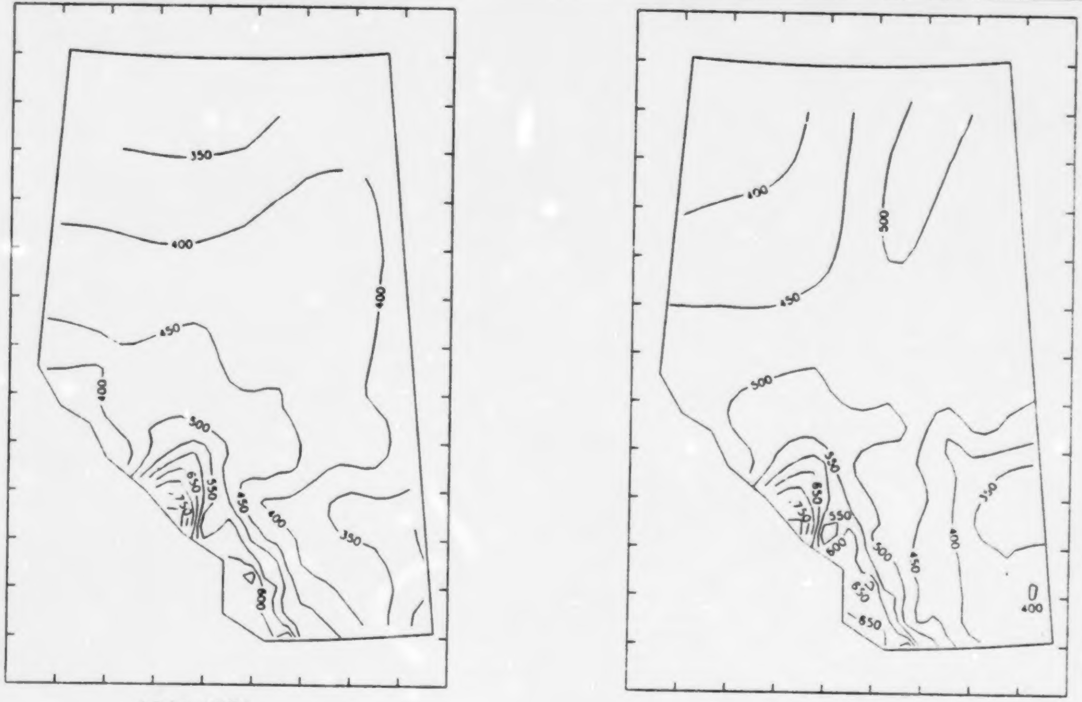
1921-1930

1931-1940

Figure 32. Spatial distributions of decadal mean (top row) and trend (bottom row) of annual total precipitation for the 1920s to 1980s. Contour intervals for the mean and trend are to 50 mm yr^{-1} and 50 mm yr^{-1} (10 yr)$^{-1}$ respectively. Ticks on the axes represent 100 km.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1941-1950

1951-1960

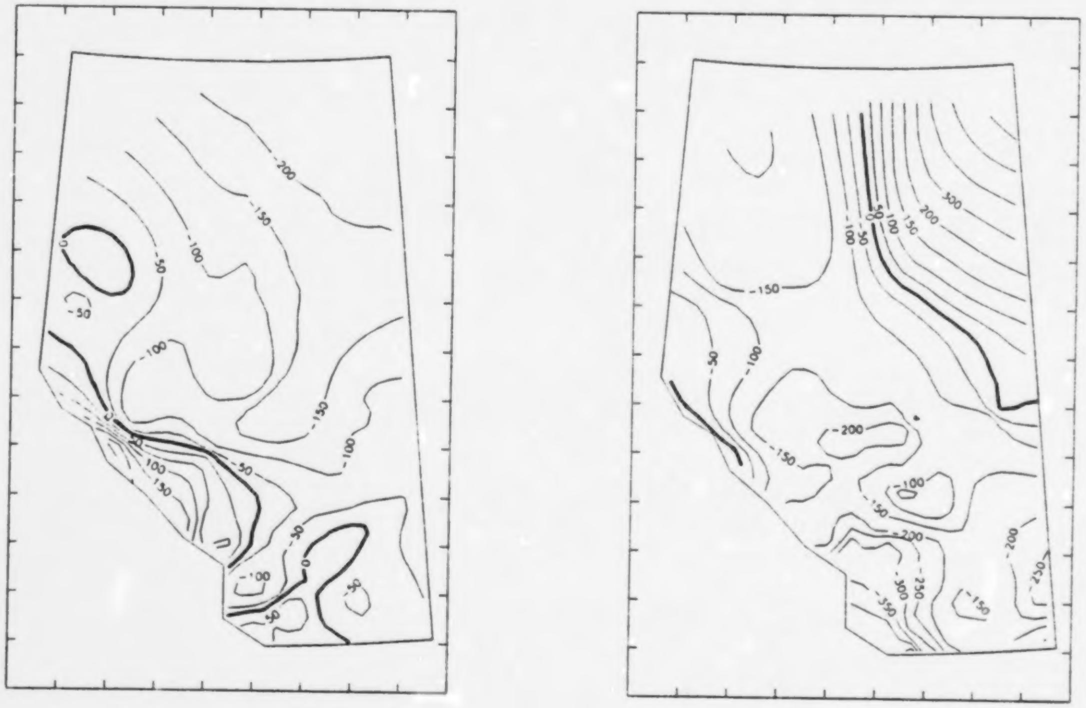
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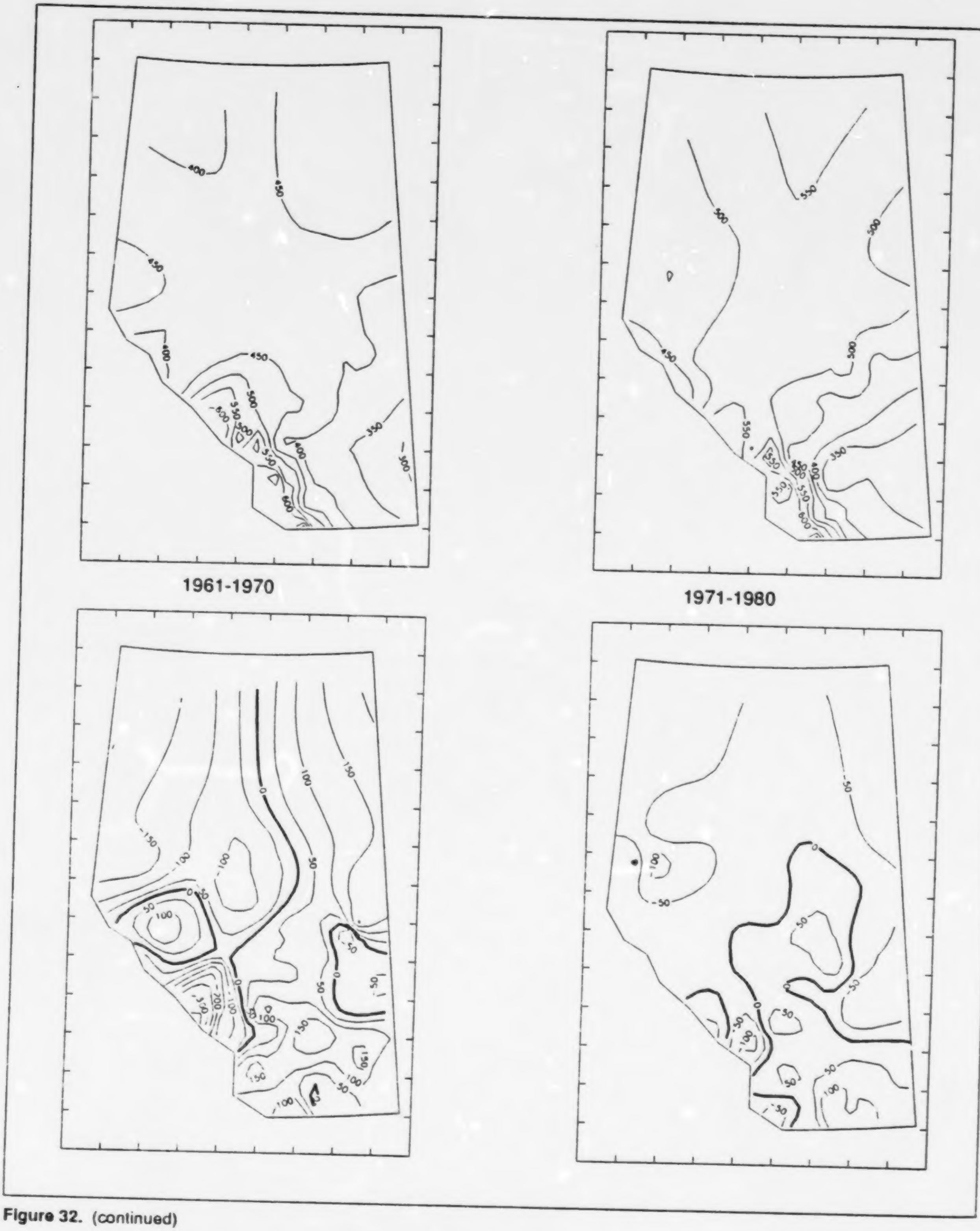
Figure 32. (continued)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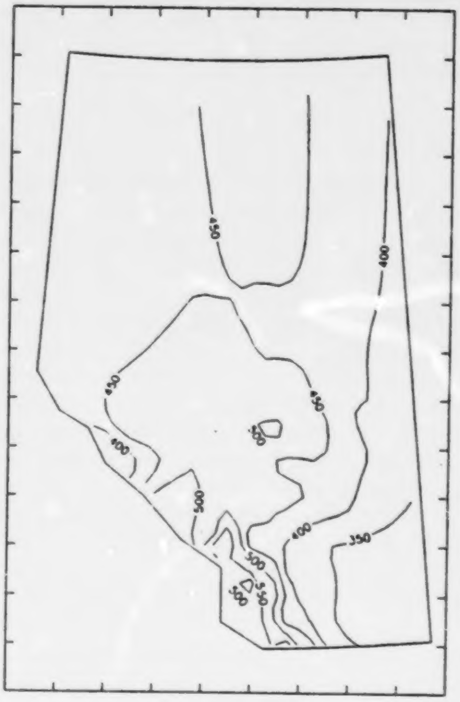
1961-1970

1971-1980

Figure 32. (continued)



1981-1987

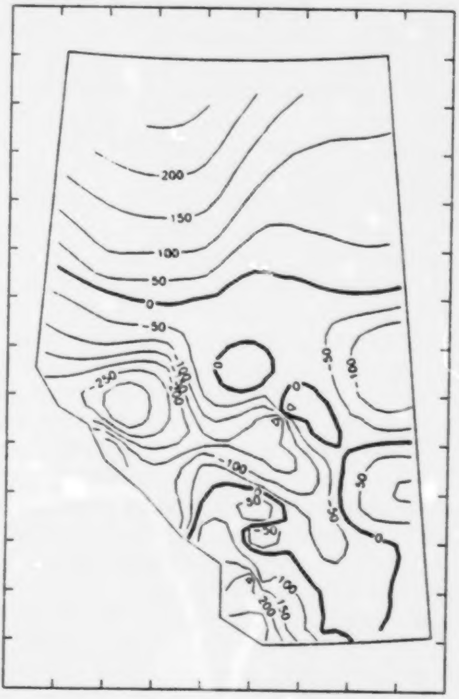


Figure 32. (continued)

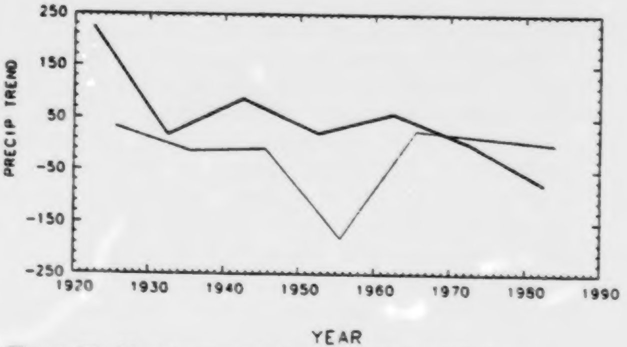


Figure 33. Alberta averaged annual total precipitation decadal trend for partition I (thin line) and partition II (thick line), in mm yr^{-1} per decade.

decreased during the same period of time. There has been no significant change in total annual precipitation. It also appears that the temperature trends have been positive and increasing throughout the record period, whereas precipitation trends varied throughout the province. The temperature range trend was negative for most of Alberta. These results are based on the data analyzed; they may be due to problems inherent in the data; i.e. the scarcity of data from some region; the irregularities in the distribution of observing stations, site relocation and the heat island effect. These results obtained so far should be verified by "cleaning" the data and reanalysis.

In the present study, a process for understanding climate change and its impacts at the provincial level was started in Alberta. It is impossible to conclusively associate the warmer 1980s climate with a globally increasing greenhouse effect. In fact, the results show some indications of an association with global warming, but the scope of the present study does not allow us to irrefutably associate these results with a greenhouse effect.

Data quality

Several factors should be kept in mind when considering data analysis for detecting climate trends. First and foremost is a good data set. This is related to the following factors: (a) In the present analysis, climate

Table 14. Summary of results for comparing trends of annual total precipitation for partition II. An asterisk above the diagonal indicates significant difference for the periods compared at the 5% level based on Dunn's method.

	18-27	28-37	38-47	48-57	58-67	68-77	78-87
18 - 27		*		*		*	*
28 - 37							*
38 - 47							*
48 - 57							*
58 - 67							*
68 - 77							

data were excluded because of incomplete records for the period of interest. Such data, however, can still contribute to an improved understanding of Alberta's climate, though more time and effort are required for interpolation and adjustment of data, and possibly more involved data processing. (b) In analyzing for long-term climate change, one is looking for a signal among fairly significant data noise. The data set must be "cleaned" prior to analysis. On a smaller scale, we have attempted such cleaning by using the double mass technique to adjust for station relocation. When one is looking at warming rates of the order of fractions of a degree per decade, however, much more detailed data cleaning procedures are necessary. At AES historical data are examined for any irregularities that may lead to data nonhomogeneity. Irregularities such as changes in the environment of the observational site, a change in observer or equipment, or station relocation can be important. Adjustments to reduce biases from such irregularities are necessary for data homogeneity.

It is tedious and difficult to prepare a good data set. It is equally tedious and difficult to identify contaminating effects such as urban warming. Wigley and Jones (1988) attempted to adjust for urban warming by making interstation comparisons between urban and rural stations. Similar investigations should be carried out on Alberta data to better differentiate greenhouse and urban warming effects. Note that our results indicate greater winter warming throughout Alberta. Although the model simulation implies that this is indicative of a greenhouse effect, it can be argued that the snow-cleared pavements and well-heated buildings of an urban area can lead to winter temperatures warmer than in rural areas covered by snow. Adjusting for biases in the temperature records due to urban warming is a necessary but difficult task.

Analysis techniques

Because of time and manpower constraints, only classical statistical techniques were used in the present study. Although distribution-free techniques were used here, climatological data are better analyzed using techniques more suitable for their characteristics. These characteristics include serial and spatial correlations that are better handled in permutation tests. Similarly, robust regression and associated analyses may be more appropriate for studying trends.

Alberta in the large-scale setting

Finally, it is useful to compare the results of climate data analysis for Alberta with those for surrounding areas. Although the emphasis of a provincial project should be on the province, the examination of Alberta's climate in relation to surrounding areas may cast light on the possible causes of climate anomalies. For example, a warming over western Canada and Alberta may not be accompanied by similar warming over eastern Canada. Such warming patterns may be related to systematic changes in the general circulation of the atmosphere, which would be useful information for the identification of possible causes.

Summary

Historical records of Alberta's climate, collected by the AES of Environment Canada, were used for the analyses. Only data from stations with continuous records for the period 1951 to 1987 were used. Because of the scarcity of data for northern Alberta, very little information for this area was included in the analyses.

In some cases, temporal nonhomogeneity in the data was caused by relocation of the observation site. Temperature records were adjusted for such nonhomogeneity; precipitation records were not adjusted.

In comparing Alberta's climate in the 1980s to that of earlier periods, three parameters were examined: mean temperature, annual average of the monthly temperature range, and total annual precipitation.

The spatial pattern of the mean temperature for the normal period (1951 to 1980) shows local maxima around Edmonton, Calgary, and Lethbridge, probably a result of the heat island effects of large urban centres.

In the 1980s temperatures were higher (compared to normal) everywhere in Alberta; the anomaly varied from 0.2 to 1.4°C. The average increase for the province is about 0.5°C per decade. This increase is statistically significant at the 10% level for most parts of Alberta.

Climate variability is represented by the annual mean of the monthly temperature range. There are increases in some areas but decreases in most areas during the 1980s. The differences are generally small and not statistically significant everywhere.

In general, the change in total annual precipitation is relatively small and not statistically significant.

Long-term trends in Alberta's temperatures suggest warming of up to 4°C per century, the average warming being 1.3°C per century. Spatial patterns of warming trends are complex; the reason for this is unknown. The temperature range trends are negative for all of Alberta except the southeastern part of the province, suggesting that temperature variability is decreasing in most parts of Alberta. The average of the temperature range trend for all the stations is -3.43°C per century. There is no predominant decrease or increase in total annual precipitation.

The average of the winter seasonal warming trend for all the stations is 2.17°C per century, almost double the value of the mean annual temperature. Averaged over all the stations, the seasonal temperature range trend is -4.88°C per century, again greater in the winter season than for the entire year. The average trend patterns for total precipitation in the winter is quite different from that for the whole year, showing again the variability of the precipitation field.

With respect to temperature, the 1980s stand out as being the decade most different from all the others. It is clear that the 1980s is a warmer period for Alberta, and the rate of warming is probably the greatest it has ever been compared with periods in the historical record of similar length. One can also say that the range in temperature has generally decreased during the same period of time. There has been no significant change in annual precipitation. Currently, it is not possible to conclusively associate the warmer 1980s climate with an increased global greenhouse effect.

User needs survey

Introduction

The objective of the user needs portion of this study was to identify the policy makers' and planners' needs for climate-based information. Specifically, the survey was designed to:

- determine the importance of climate variability and possible change on strategic departmental planning,
- assess whether short- or long-term climate information is more important for departmental planning,
- identify the principle climate parameter(s) required for planning needs,
- note deficiencies in current climate information for planning purposes,
- identify the provincial and external geographic areas for which climate information may be required for planning purposes, and
- identify useful planning tools.

The survey was not expected to result in a detailed user specification for the climate-based data being used by the participating departments. An analysis of total usage and requirements would require a detailed study involving all departmental staff that use climate data. Despite the number of survey participants, the selection of individuals for this project was not uniform or complete. Some departments did not have representatives from all their divisions, and additional individuals were identified during the interview process for possible future interviews.

The remainder of this chapter describes the survey process, the indicators of climate data requirements and deficiencies, and user-specified interest in short- and long-term climate data. Models, either currently used or requested, are also discussed. The results are presented as indicators of usage within departments. For example, a value of 0% reflects low usage, not necessarily zero usage within the department. Given the selection process and representation within departments, the values do not reflect absolute usage.

User survey process

The user needs survey was based on a standard questionnaire, included in Appendix C. The questionnaire was developed by Alberta Research Council staff and validated by a steering committee subgroup. All interviews were scheduled and conducted by a team of Research Council staff. Following the interviews, the completed questionnaire was returned to the participant(s) for validation.

The questionnaire, composed of four logical sections, was designed to provide an overview of managerial interest in climate-based data. The first section was included to obtain an understanding of the activities or programs for which the person is responsible, and their perception of how climate affects those activities. The second portion, questions three through seven, deals with the actual climate-based information used by the person or group, the time and space scales, the desired data formats, and the relative importance of the specified parameters. Questions about perceived or actual deficiencies in the available data are also included in this section. The third section of the questionnaire addresses the relative importance of short- and long-term climatic information to the individual's program(s) or areas of responsibility. The aim of the last section was to identify planning tools that the respondent is using or would like to use.

Because of the limited time frame for this project, interviews were conducted only with staff from Alberta Agriculture; Alberta Forestry, Lands and Wildlife; and Alberta Environment. Representatives from Alberta Technology, Research and Telecommunications requested that they be excluded from the interview process as they are not active users of climate-based information. The Research Council has postponed staff interviews to a later date.

Survey participants were selected by the steering committee representatives, each of whom was asked to identify ten individuals within their department. The selection of individuals was neither random nor standardized. Most of those selected either participated or identified others who could participate in the survey. Thirty interviews, each with duration of one to two hours, were conducted between March 1, 1989 and May 19, 1989 (Table 15).

Table 15. Survey participation.

Organization	Number of Interviews	Number of participants
Alberta Agriculture	11	32
Alberta Forestry, Lands and Wildlife	8	10
Alberta Environment	11	21
Total	30	63

The size of the interview group ranged from one to six individuals; a total of 63 people were interviewed. A complete list of interview participants is given in Appendix D.

Climate-based data requirements

This section addresses the general user-identified requirements for climate data. Included are the following data aspects: identification of current data used, an assessment of the key parameter(s) for planning, and the general time and space requirements necessary for planning or operations.

As previously noted, these results are planning indicators only and do not represent a comprehensive summary of data use. The sample size, survey limitations, and questionnaire design preclude a detailed analysis of climate data use.

The level of use of climate parameters is presented in Figures 34 to 37. These graphs indicate the percentage of departmental respondents using a specific parameter. Parameters are sorted from top to bottom by increasing value and each bar is labelled with its associated percentage. Nonspecified parameters are identified by a zero ('0') value on the graph, indicating little or no usage.

A climate parameter was included if it was either explicitly indicated for operations or suggested in the general planning procedures. Some parameters are closely related but were identified separately to help reflect the different emphasis of respondents. An attempt was made to ensure that most parameters consciously used for planning were identified. Some parameters that are not widely measured, such as soil moisture or evaporation, may be significantly represented even though actual values were not available or directly used. These graphs only represent the frequency that a parameter was acknowledged and do not indicate actual importance.

Whenever possible, individual responses by departmental representatives were used. In interviews involving more than one staff member, a consensus answer was assigned to each staff member when appropriate. In interviews where there was a difference of opinion among staff members, separate responses were recorded.

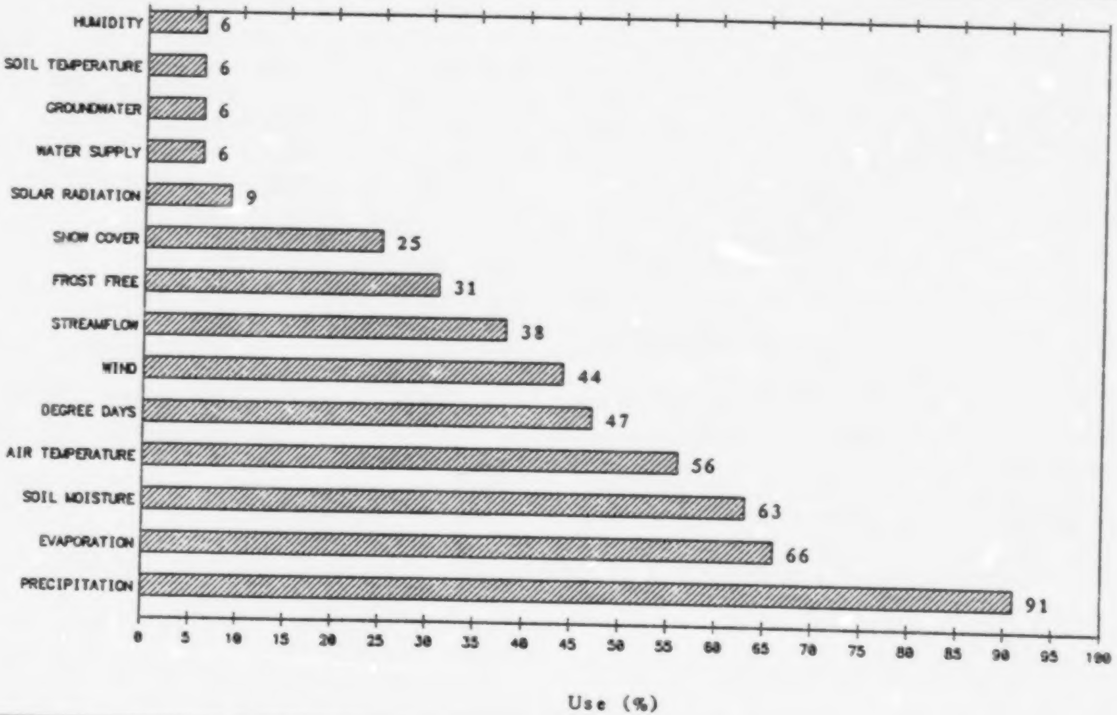


Figure 34. Alberta Agriculture. Climate data used.

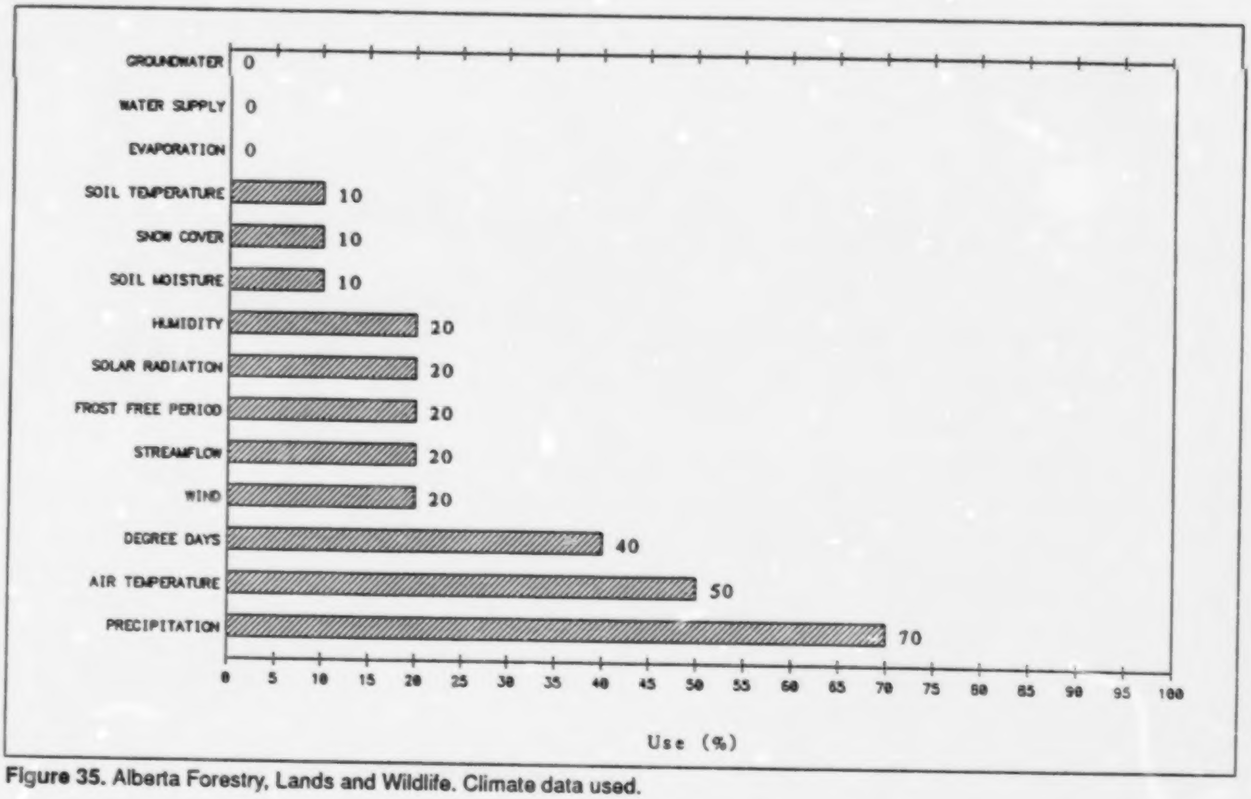


Figure 35. Alberta Forestry, Lands and Wildlife. Climate data used.

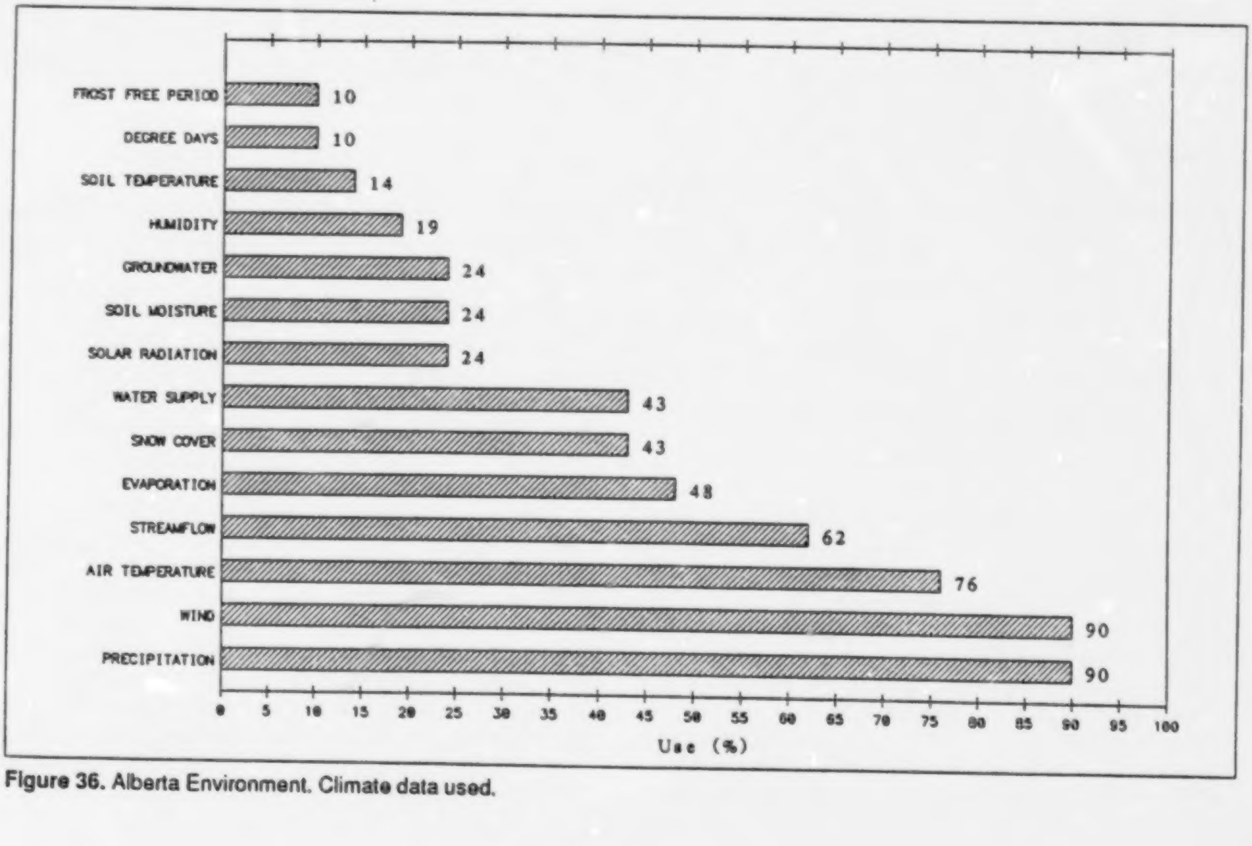


Figure 36. Alberta Environment. Climate data used.

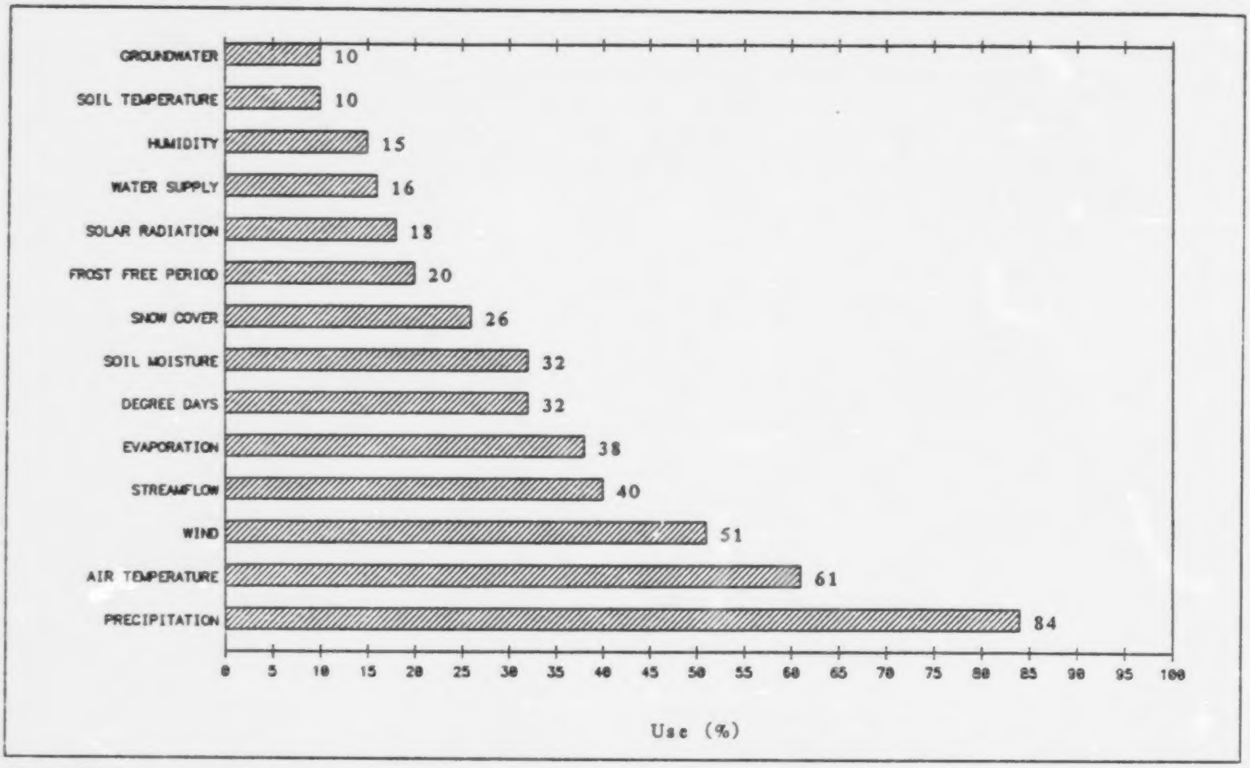


Figure 37. Summary of all departments interviewed. Climate data used.

The differences in the responses reflect the different mandates of the departments. The results for Alberta Agriculture (Figure 34) indicate a strong use of precipitation information, followed by evaporation, soil moisture, and air temperature data. The emphasis on water and energy reflects the sensitivity and planning concerns for agricultural production.

The results for Alberta Forestry, Lands and Wildlife are reported in Figure 35. The smaller sample size is reflected in the more selective identification of parameters. The importance of precipitation and energy for forest production and land management remains evident. Other factors include humidity and wind parameters, which are important for forest protection purposes. The concerns for wildlife management and habitat protection are reflected in the need for streamflow data.

The results for Alberta Environment (Figure 36) are indicative of the wide range of activities undertaken by that department. Environmental monitoring and water management have a strong influence on the precipitation, wind, temperature, and streamflow data requirements for the department.

A summary of all three departments is presented in Figure 37. This summary represents an unweighted average of the results for the three departments. By using this average, each department is ranked equally and the aggregated responses caused by the different departmental representation are not skewed. The disperse results reveal the overall variety of interests of the individual departments surveyed. Precipitation continues to be the dominant factor for all three departments. Air temperature is a common interest and is rated second. The importance of wind and streamflow data for Alberta Environment ensures that those parameters remain relatively important overall.

Key climate-based parameters

The key climate parameters identified by survey respondents are listed in Table 16. The table shows the number of respondents who identified a given priority for a specific parameter. In addition to the top priority, secondary and tertiary priorities are listed when specified by respondents.

The table does not provide a ranking of all parameters, as the purpose was limited to identification of top-priority parameters only. Lower priority parameters are included only when explicitly identified by respondents. Consequently, the relative importance of parameters other than those identified as "most important" cannot be determined.

The identification of key parameter(s) also differs significantly from the climate data used illustrated in Figures 34 to 37. The previous graphs identified parameters currently used but provided no indication

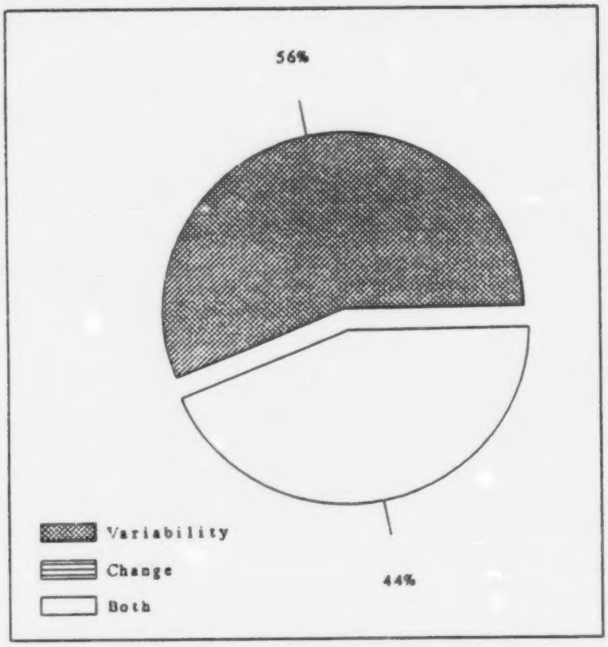


Figure 38. Alberta Agriculture. Principal interest: climate change or variability?

of their relative importance. In contrast, Table 16 identifies the most important parameters but does not indicate whether they are being actively used or collected. Certain parameters that are routinely collected or used (e.g. humidity) may not be ranked very highly in Table 16 if they are considered to be less important. Similarly, some parameters (e.g. evaporation) may be highly ranked in importance even if they are not widely used.

The first three portions of the table present the results by department, with parameters listed by relative priority. The fourth section provides a summary of the combined responses from all three departments. This summary lists total values only and is heavily weighted by the number of respondents from Alberta Agriculture and Alberta Environment. The absence of complete ranking data does not permit valid standardization of responses by department. The key climate parameter for all three departments is precipitation.

These results reflect the different mandates of the departments. The importance of seasonal data for Alberta Agriculture and daily data for Alberta Environment is evident. Forestry, Lands and Wildlife needs both very short or real-time data for forest protection and long-term information for reforestation and land use planning. The need for environmental monitoring is suggested by Alberta Environment's requirement for hourly and daily data. In general, daily and seasonal periods are the most important scales for operations and planning.

Table 16. Key climate parameters.

	Parameter	Identified priority		
		#1	#2	#3
Alberta Agriculture	Precipitation	17		
	Evaporation	6	2	1
	Soil moisture	2	6	
	Air temperature	4	2	
	Ground water	1		
	Degree days		3	
	Wind		1	
Alberta Forestry, Lands and Wildlife	Precipitation	5		
	Degree days	1		
	Soil temperature	1	2	
	Humidity		2	
	Soil moisture		2	
	Evaporation		1	
	Frost period		1	
	Wind			2
Alberta Environment	Precipitation	9	3	1
	Air temperature	3	7	
	Wind	3	2	1
	Stream flow	2	2	
	Snow cover	2		
	Water supply	2		
	Humidity		4	
	Evaporation		2	
	Soil moisture			3
Departmental Total	Precipitation	31	3	1
	Air temperature	8	9	
	Evaporation	6	5	1
	Wind	3	3	3
	Soil moisture	2	8	3
	Stream flow	2	2	
	Snow cover	2		
	Water supply	2		
	Ground water	1		
	Degree days	1	3	
	Soil temperature	1	2	
	Humidity		6	

Time scales for climate-based parameters

The time scales used or required for operational or planning purposes are summarized in Table 17. The time frequency scales are defined as follows:

Now – near real-time current conditions (e.g. on-line access to current water flow levels, storm systems).

Hourly – archived hourly measurements (e.g. AES first-order station data).

Daily – archived daily climate values or forecasts (e.g. AES climate station temperature, precipitation data).

Weekly – weekly summaries or forecasts of climate conditions (e.g. precipitation summaries, 5-day forecasts).

Monthly – monthly averages of climate conditions (e.g. AES climate normals or monthly summaries).

Seasonal – summaries or forecasts of climate conditions for a specific, activity-related parameter (e.g. winter snowpack, spring soil moisture).

Annual – yearly summaries of climate conditions or averages (e.g. annual precipitation).

Years – forecasts or summaries of climate data (e.g. 3 to 5 year averages, drought summaries).

Decades – long-term forecasts or averages of climate conditions (e.g. climate change scenarios, 10-, 20-, or 30-year conditions).

Table 17 gives a summary of the use (as a percentage) and the unweighted average for the three departments.

Space scales for climate-based parameters

The spatial scales necessary for operational and planning purposes are examined and summarized in Table 18. The assignment of various geographic scales is difficult as their definition varies according to the user. The following scale descriptions are general definitions for each category:

Plot – site-specific location or research plots.

Local – farms, townships.

Subregion – farming districts, river sub-basin, ecological reserves.

Region – provincial administrative areas, ecoregions.

Province – province-wide management, adjacent provinces or states.

Global – agricultural or forested regions of other nations.

Geographical scales are reported in Table 18 in terms of percentage use for the departments. The unweighted average of the three departments is an indicator of overall importance.

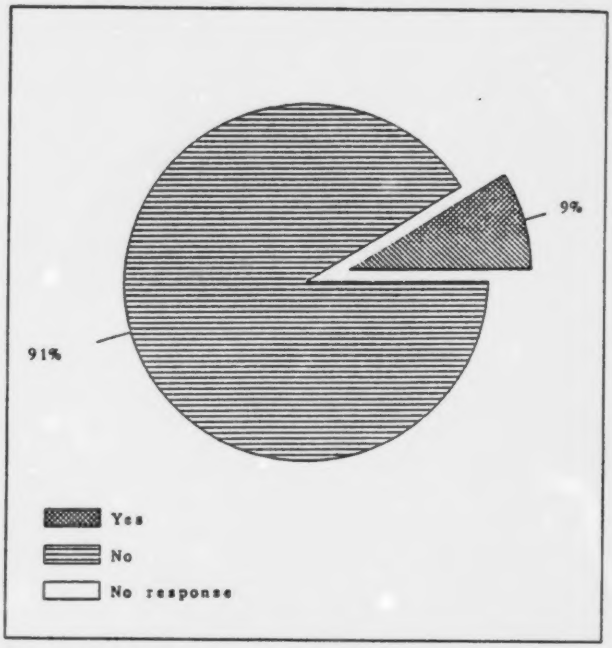


Figure 39. Alberta Agriculture. Importance of advance warning.

Survey results suggest that there is a higher degree of overlap in the spatial scale requirements for the three departments than in the time scales. In all three cases, the most important spatial scale is sub-regional information, followed closely by regional, then local. The environmental monitoring requirements of Alberta Environment are reflected in the demand for small-scale, site-specific information.

Climate change and climate variability

Departmental interest in short- and long-term climate data was explicitly discussed during the interviews. The results are summarized in Figures 38 to 45. These pie charts identify which of the following parameters is of greater concern to departmental staff for planning or operations: climate change, variability, or both. In Figures 39, 41, and 43 the importance of

Table 17. Planning and operational time scales (percentage use).

	Now	Hour	Daily	Weekly	Monthly	Seasonal	Annual	Years	Decades
Alberta Agriculture	19	0	28	19	16	59	19	19	19
Alberta Forestry, Lands & Wildlife	20	20	30	10	10	20	0	0	40
Alberta Environment	10	43	52	24	33	24	38	10	5
Average	16	21	37	18	20	34	19	9	21

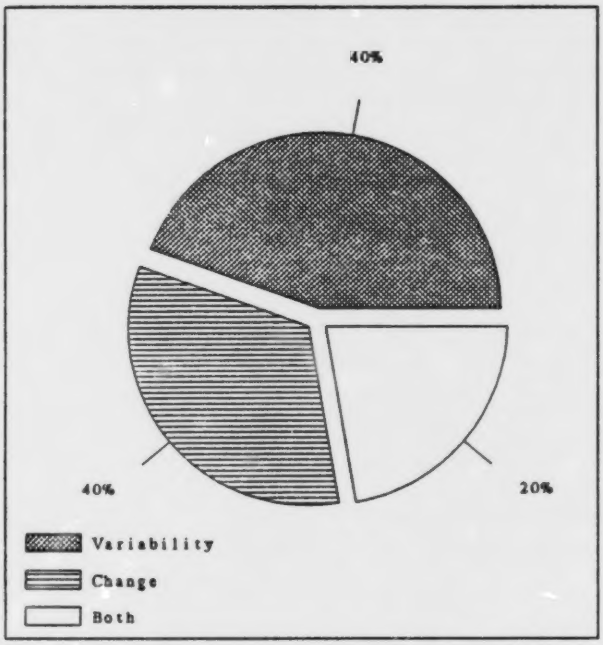


Figure 40. Alberta Forestry, Lands and Wildlife. Principal interest: climate change or variability?

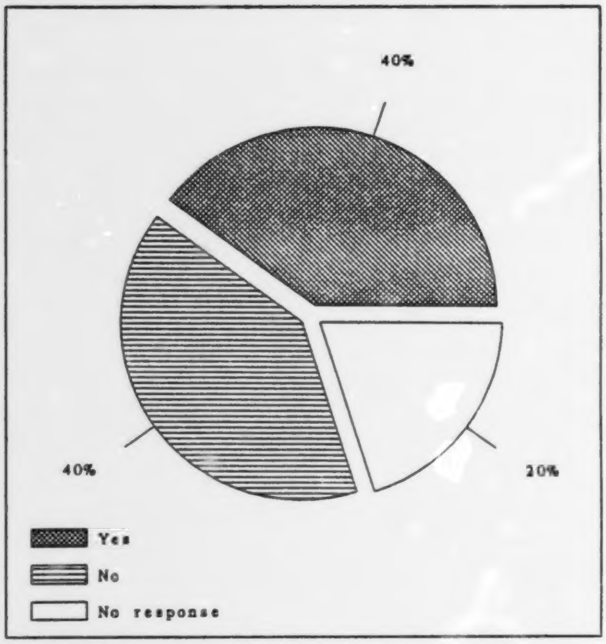


Figure 41. Alberta Forestry, Lands and Wildlife. Importance of advance warning.

advance warning of possible climate change for departmental planning purposes is indicated. There is a noticeable variation among departments. These differences reflect the different mandates and responsibilities of the three departments interviewed.

Climate variability is of greater concern for Alberta Agriculture, (Figure 38). Notably, none of the 31 departmental respondents identified climate change as the paramount concern for planning; however, 44% of respondents did indicate that climate change should be considered in the planning procedures. Advance notice of change (Figure 39) was not a priority for more than 90% of respondents. The mandate of Alberta Agriculture provides an annual focus on production, reflecting rapidly changing market conditions and producer choices.

The responsibility of Alberta Forestry, Lands and Wildlife for natural resource and land management covers a wide range of time scales and priorities. As shown in Figure 40, there is an equal split between the ranking of climate change and climate variability. This equal weighting is carried over in the need for advance warning (Figure 41). Longer term concerns for forest and land management are balanced by the shorter term, operational needs of forest and wildlife habitat protection and reclamation activities.

Alberta Environment's mandate for environmental protection and water resource management has a mid- to long-term focus. This is reflected in an increased interest in climate change issues. While variability remained the prime concern, almost 60% of respondents expressed interest in climate change (Figure 42). In addition, a slight majority of respondents (52%) indicated that advance warning of climate change was required for their planning processes (Figure 43).

The simple, standardized, average results for all three departments are given in Figures 44 and 45. The general consensus is that climate variability is the most important concern, but potential climate change

Table 18. Planning and operational spatial scale (percentage use).

	Plot	Local	Subregion	Region	Province	Global
Alberta Agriculture	3	38	63	50	31	13
Alberta Forestry, Landsand Wildlife	10	40	60	50	10	0
Alberta Environment	24	38	52	38	38	0
Average	12	39	58	46	26	4

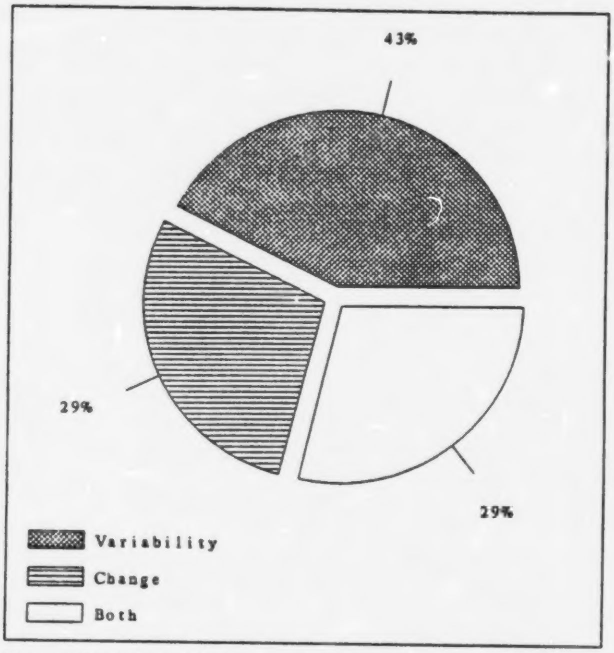


Figure 42. Alberta Environment. Principal interest: climate change or variability?

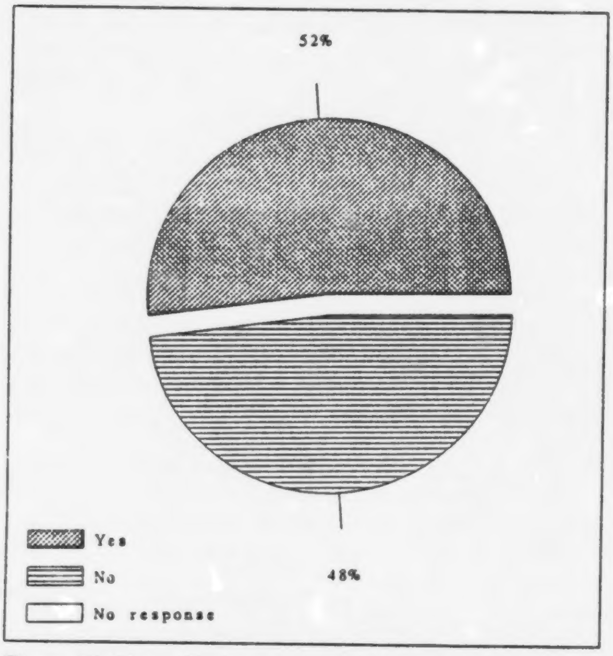


Figure 43. Alberta Environment. Importance of advance warning.

remains an important issue for more than 50% of respondents. Approximately one-third of the staff surveyed required advance notice of possible climate changes for their planning needs.

Table 19. Climate information concerns.

	Agriculture	Forestry Lands and Wildlife	Environment
Networks/Parameters:			
Improved Network Density			
northern Alberta	y	y	y
agricultural Regions	y		
mountains		y	y
remote areas			y
Climate Parameters			
water supply	y	y	
solar radiation	y		
subsoil moisture	y	y	y
soil temperature		y	y
precipitation	y		y
evaporation	y	y	y
atmospheric stability, inversion & turbulance			y
frost free days	y		
temperature		y	
winter snowpack		y	
hourly averaged wind			y
growing degree days		y	
Forecasting:			
Improved regional and subregional Forecasting			
three to five days	y	y	
five to ten days	y		
seasonal	y	y	y
winter intensity	y		
Longer term Forecasting			
medium (2 weeks-1 month)	y		
long term (seasonal plus)	y		y
quarterly (international)	y		
Forecast Parameters			
precipitation	y	y	y
spring runoff		y	y
spring drought	y	y	y
long term drought	y		y
temperature	y		
lightning Forecasts		y	
Communication:			
data archive/access	y	y	y
data analysis/interpretation	y	y	y
educational information	y	y	y

User specified climate information concerns

During the survey, participants were specifically asked whether they had access to all the climate-based data necessary to support their operational and planning activities. Their concerns with the available data have been grouped into three general categories: networks/parameters, forecasting, and communications. Networks/parameters are deficiencies in specific weather measurements and the monitoring network density or location. Forecasting includes short- and long-term predictions of weather conditions. Communications issues raised by users included the interpretation and dissemination of climate-based information. The users' responses (Table 19) have not been quantified. Some points were raised once, others frequently. Any user-identified need or deficiency is indicated by a 'y' in the table.

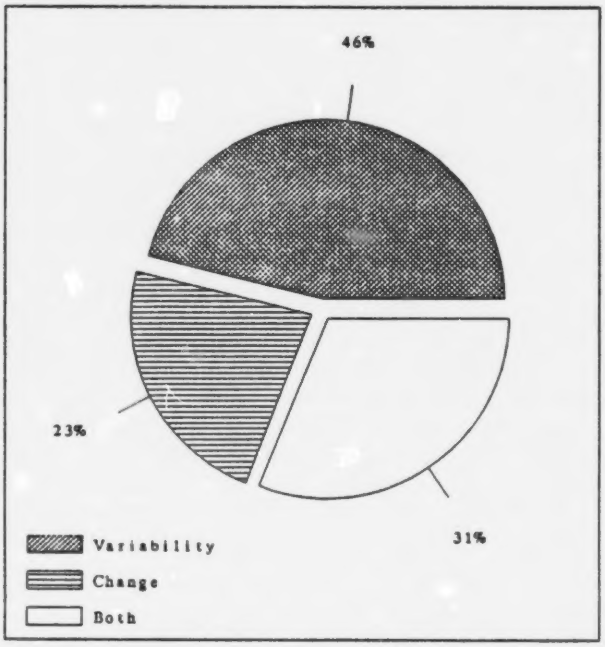


Figure 44. Summary of all departments interviewed. Principal interest: climate change or variability?

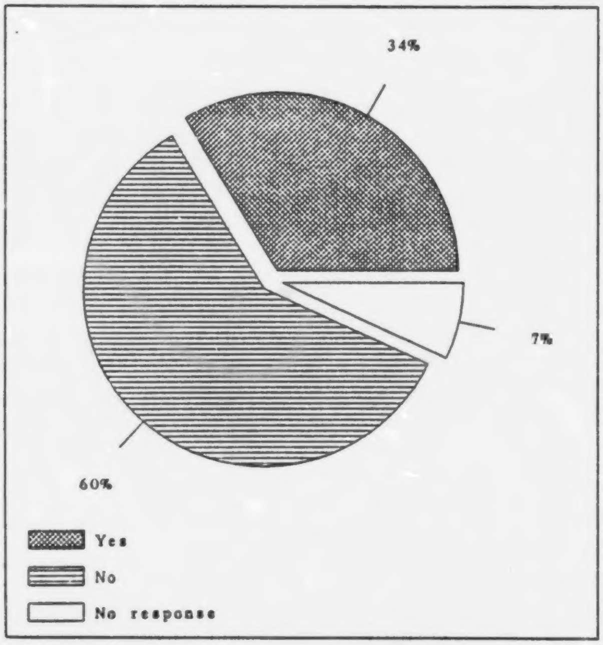


Figure 45. Summary of all departments interviewed importance of advance warning.

Although the frequency of climate observations is generally sufficient, the network density and/or location of weather monitoring stations for specific regions, especially northern Alberta, are inadequate. Alberta Agriculture and Forestry, Lands and Wildlife have insufficient climate-based data to support current agricultural and forestry expansion in northern Alberta. Users need both current data and long-term historical data bases from which they can extract normal values and variability data for planning purposes. Because

Table 20. Climate-based planning support tools for departments surveyed.

Models	Agriculture	Environment	Forestry, Lands & Wildlife
Vegetative Production	U		
Crop/forage yield	U		
Production at high elevations			R
Soil Moisture Availability/Production	R		
Pest Management			
CLIMAX		U	
Grasshopper infestation	U		
Insect infestation	R		
Soil Conservation			
Soil Degradation	R		
Soil Erosion	U,R		
Soil Conservation/ Production	R		
Salinization model			
Terrain/climate			R
Salinization		U	
Water Availability			
Groundwater Regeneration	U	U	
Water Supply model	U*,R	U	
Hydrologic models (flood forecasting, etc.)		U	
Stream Flows	R	U	U
Reservoir Basin model	U	U	
Seasonal precipitation			R
Evapotranspiration	U	U	R
Water Quality			
Water Quality (WQRR1)		U	U
Temperature modelling (stream flows)			U
Air Quality			
Sour Gas dispersion		U	
Dispersion models		U	
Others			
Supply Modelling	U		
Canadian Fire Weather Index			U
Risk assessment	R	R	R

* The model used by Agriculture is the Alberta Environment model.

this data is unavailable, land use studies, water management projects, and environmental assessments rely on extrapolated data, possibly affecting the validity of the studies. Better spatial coverage is necessary to improve the quality of extrapolated data.

The Forest Protection Branch and Alberta Environment also identified some gaps in their networks in the mountain areas and in northern and eastern Alberta. A number of the Forest Protection Branch stations are located at the manned ranger stations at higher elevations resulting in inadequate coverage for the valleys and lower elevations. In addition, these stations are operated on a seasonal basis and because monitoring often begins after spring runoff, the data base is incomplete. Lack of funding prevents Alberta Environment from improving their monitoring network in northern and eastern Alberta.

Alberta Agriculture would like better coverage throughout the agricultural regions. They identified two key problem areas: (1) In northern Alberta there is a need for improved network density and placement of monitoring stations to support agricultural expansion in that region. Derived parameters such as degree days are not available for some of the newer areas. (2) Given the extreme climatic variability in southeastern Alberta, the standard network density is inadequate.

The spatial regions for the large-scale networks operated by AES and Alberta Environment are too coarse for a number of groups. All three departments surveyed are involved in site-specific activities, which may not be supported even with improved AES/Alberta Environment coverage. These sites tend to be problem areas or test sites on a local or farm level. For some of their projects, the groups have installed monitoring stations and they monitor climate for periods of from one season to five years. Two small networks, operated by Forestry, Lands and Wildlife in southeastern and northern Alberta, may become permanent. When monitoring stations cannot be installed on the site, data from the nearest AES station is extrapolated. In some instances, the extrapolated data is inadequate and the work has been postponed.

There are also a number of climate-based parameters for which existing data is inadequate or nonexistent. Of these parameters, the most frequently requested data is precipitation-related. Specific problems with existing precipitation data included incomplete spring runoff data, inaccuracies in measurements due to older monitoring technology, and inadequate coverage for certain regions. Alberta Agriculture would like better precipitation intensity, quantity, and timing measurements on a local scale to support their water resource management, crop management, and soil conservation programs. Alberta Environment uses precipitation intensity data for flood forecasting and emergency cleanup situations. Precipitation data for the irrigated regions is required for the water management programs to determine water demand. This type of data is not a concern of Forestry, Lands and Wildlife. The Forest Protection Branch maintains a large monitoring network for collecting the precipitation data required for their Canadian Fire Weather Index. The research groups within Forestry, Lands and Wildlife are more interested in water table levels because many of the forested areas in Alberta have water levels that are too high. This increases soil erosion problems and hampers reclamation and reforestation projects.

The development and enforcement of air and water quality standards are a large component of Alberta Environment's responsibilities. Improved time and spatial resolution is necessary for obtaining better atmospheric stability and inversion data. For example, hourly averaged wind rather than the current spot wind measurements are needed. There is limited turbulence data available and it does not appear to have been archived and is therefore inaccessible to users.

Soil temperature, soil moisture, and solar radiation are used to estimate vegetative growth, and users would like improved spatial and time resolution. They also indicated a problem with existing technology for soil moisture measurements. One of the limiting factors in forest reclamation programs is soil temperature. Because of the seasonal nature of their data, neither the spring soil temperature nor the growing degree days can be determined.

There is a lack of usable or reliable weather forecast information. Those managing operational activities would like three to five and five to ten day forecasts with an accuracy of 70% or better. Alberta Agriculture requires that the forecasts be more regional, especially for areas of high variability. Alberta Environment projects involving emergency cleanup are based on a worst case scenario and current short-term forecasts are therefore adequate.

The longer term forecasts related to water supply and demand are very important for all three groups. Changes in drought frequency and magnitude would have major implications for Alberta Environment's water allocation planning. Using historical data, current water allocation and reservoir planning incorporate drought cycles, with rejuvenation periods between cycles. In some areas of southern Alberta, all available water has been allocated and future climate changes could require modified dam and reservoir planning. The sustained growth policy of Forestry, Lands and Wildlife is also based on historical data and may need to be reevaluated before the first cut is completed if there are significant changes in either temperature or precipitation.

Communication issues tended to focus on data archiving, access, analysis, and interpretation. There was some concern that data collected by a number of groups is not archived or accessible to other users.

Specific examples include turbulence data, industrial data, and data from mesoscale networks operated by various departments. Access requirements range from provision of expertise to on-line access to the raw data. Some users did not know whom to contact or what type of data to ask for, and as a result, they were unaware of what they could use effectively. In some cases, there is a need for expertise in providing better compilation of data and data extrapolation. Professional statistical support is necessary for consistent interpretation of existing data. On the other hand, some users were much more independent and only required access to the data as their analyses and interpretations were being performed by in-house experts or external consultants.

Users generally wanted more information about climate change and climate variability, but were concerned by the lack of scientific consensus and the lack of regional predictions for Alberta. Although existing data would not be used for current planning because of the low level of accuracy, interviewees requested up-to-date, easy-to-read literature reviews describing GCMs and climate change scenarios. There was also great interest in the impact of climate change on the frequency and magnitude of climate variability. This type of information is needed on an ongoing basis and will be used for planning once there is evidence that the changes are actually going to occur.

Several of the groups interviewed recommended the establishment of a centralized group responsible for the archiving, interpretation, and dissemination of climate-based data. These people would act as a resource group and could provide varying degrees of support for the users of climate-based data.

Planning tools

Responses to the questions dealing with planning tools emphasized the need for integration of climate-based parameters in predictive models for water availability, water quality, and vegetative production. Some of the models, either in current use or those that would be useful support tools for planning activities are listed in Table 20. Models currently being used within a department are flagged with a 'U' for 'using'. Models to which the group would like access are indicated by an 'R' for 'requested'.

There are significant areas of overlap among the three departments surveyed (Table 20). Both Alberta Agriculture and Forestry, Lands and Wildlife use or would like to use vegetative production models. Forestry, Lands and Wildlife requires models for estimating forest regeneration periods in high altitude areas because desiccation can result in significant changes in regeneration time. Alberta Agriculture is interested in production models, both from a soil conservation and a production perspective. They would like models that are capable of estimating the appropriate production levels necessary for soil conservation.

Increased modelling capabilities are required for estimating water availability, water flow, and soil erosion. Alberta Environment is responsible for the allocation of water and therefore must be able to model the supply in order to allocate this limited resource effectively. The agriculture industry would like to know that sufficient water supplies are available to meet their crop demands. Modelling is being used to estimate regional soil erosion based on soil moisture and wind conditions. Users would like to extend this work to include the relationship of climatic data to production and soil conservation. Computer models are also used to forecast the water supply required to supplement surface water for the dugout program.

A common concern involves the lack of available climate-based input parameters. This limits the ability of the model to support agricultural and environmental risk assessments. In some instances, modelling projects have been postponed because of inadequate input data. Rather than means or normals, some users would prefer probability estimates with better than 70% accuracy. This would permit them to use models to identify potential risks and repercussions for various climate scenarios. For example, warming trends can have a major effect on plant breeding and sustainable production (agriculture and forestry). One of the groups interviewed would like to link GCMs to crop production models. Others requested regional impact models, which report the probabilities or risks for certain climate scenarios under current climatic conditions.

Insect infestation modelling for identifying potential insect infestation areas based on climatic conditions and natural predators was desired by some people. Key concerns included wind patterns and changes in conditions that might inhibit the survival of foreign species carried into Alberta.

Overall, there was a great deal of interest in the use of models to support both short- and long-term activities. The level of sophistication of modelling ranges from intuitive models to computerized models. A number of groups within Alberta Agriculture and Alberta Environment are involved in joint projects, which has resulted in an informal network of internal and external resource people. There are still groups within departments who would like to use modelling capabilities that currently exist within their own departments or in other government departments and organizations. If this informal network is expanded and strengthened, it could support these groups and may be able to expand access to modelling by addressing personnel and financial constraints.

Summary

A number of observations from the user survey are listed below. There is no implied ranking in the order.

1. The survey was designed to identify the key climate-based data necessary for planning. Although the results are indicators rather than actual use within the departments, they provide a good understanding of the type of data required by each department. A detailed study involving all users of climate-based data is necessary to define the actual usage within the departments.
2. The key climate-based parameters are precipitation and water-related information. Users are very concerned about the climate impacts on water availability and water quality.
3. Short-term climatic information is important for the majority of users. Their concerns focused on the impact of climate variability on departmental activities. Long-term climatic effects, however, remain important for more than 50% of the users.
4. The time and spatial resolution for climate-based data is project dependent. In general, operational activities require high-resolution time and spatial scales. The preferred scales are subregional or regional and on a seasonal basis. Planning data can be provided on a coarser scale.
5. There are deficiencies in the time and spatial scales for the large-scale monitoring network. Some of these deficiencies can be addressed through the use of modern technology and improved coverage. Some users, because of the site-specific nature of their activities, may not be accommodated even with improved coverage of large-scale networks. It is hoped that AES weather radar will improve the general coverage in Alberta.
6. Archiving, access, analysis, interpretation, and dissemination of existing data can be improved. Weather monitoring is carried out by a number of groups but the data is not archived or accessible to others. Access to current and archived data is not fast enough for some activities, and trained support staff are required to provide professional and consistent analysis and interpretation of existing data.
7. There are high levels of interest and demand for models utilizing climate-based data. This demand appears to be increasing, and users will require more and better climate-based input data.
8. The validity of the GCMs and the climate change scenarios were questioned by most users. To be usable for planning purposes the model scenarios must have a 70% or better confidence rating. Most staff interviewed felt, however, that the GCM work is valuable and they would like continued access to information about climate change and scientific opinion written in layman's terms.
9. Risk assessment models are being used to identify risks using historical data. To estimate future risks, users may be able to use GCM outputs in their own models. GCMs can produce precipitation, temperature, hydrology, and soil moisture scenarios. Although the hydrology and soil moisture values are primitive, the model results may provide interesting future scenarios.
10. There is a general impression among the individuals surveyed that climate change will be gradual. The indicators in this report reflect this assumption, since most groups felt that they could adapt to a gradual climate change.
11. In the activities of the different agencies there is a wide variation in the time requirements necessary to adjust to climate changes. For example, crop development may take up to a decade and the rotation time for reforestation is greater than 100 years.
12. There is a minor concern that not enough emphasis has been placed upon the impact of climate on society. Land use and water allocation are based on historical or extrapolated data and the resulting decisions may have major implications for the provincial and municipal governments.

Implications for developing a strategy for adapting to climate change in Alberta

Introduction

There is a general consensus among scientists that greenhouse warming on a global scale is increasing. This belief is supported by data from long-term monitoring of atmospheric CO_2 and GCM simulations. Although the indications for increased greenhouse warming on a global level are strong there is no absolute proof and disagreement still exists over how much warming is caused by increases in greenhouse gases, and where and what the effects will be. The indications are strong enough, however, that serious concerns about major climate changes have been raised. This is apparent in the increased frequency of international meetings on climate change, particularly within the past year. Among these were the "Conference on the Changing Atmosphere: Implications for Global Security", held in Toronto, 27-30 June 1988, the "Meeting for the Protection of the Atmosphere: Meeting of Policy and Legal Experts", held in Ottawa, 20-22 February 1989, and the "Conference to Adopt the Hague Declarations", held on 11 March 1989 and attended by twenty-four heads of state including Prime Minister Brian Mulroney.

On a regional level, the degree of uncertainty about whether or not greenhouse warming is occurring is even greater. From our analyses of Alberta's climate data and the GCM simulation results, it is difficult to assess the effects of climate change, if they actually occur. This, however, should not lessen our concerns about climate change. The effects of this change will be felt in Alberta before enhanced greenhouse warming is proven. Although atmospheric CO_2 doubling has been estimated to occur by 2030 to 2050 A.D. significant effects will be felt long before then. It is also possible that relatively abrupt changes may result from gradual warming.

The present study grew out of concern about possible climate change in Alberta. The study comprised (a) an assessment of the results of climate models with respect to what they predict for Alberta; (b) an analysis of the climate records of Alberta to determine whether there is any evidence that Alberta's climate is changing, and (c) identification of user needs for climate-based information in order to develop strategies for adapting to climate change in Alberta. The detailed results of these tasks are summarized at the end of the respective chapters. In this chapter, the results are examined for their implications on strategy development.

With respect to available climate model (GCM) results, we will address the following questions:

1. What do the GCM results say for Alberta?
2. What are the strengths and weaknesses of GCMs?
3. Can results or simulations from GCMs be modified so as to take into account Alberta's landscape and other regional features?
4. Are the GCMs useful for planning or strategy development for Alberta?

With respect to the examination of Alberta's climate records for indications of climate change, the following questions will be asked:

5. Is Alberta's climate changing?
6. By how much and how quickly has the climate changed?
7. What are the regional differences in climate within Alberta?
8. Will the frequency of extreme temperature and rainfall events change in Alberta?
9. Will the magnitude of these events change?

From the user needs study we hoped to be able to address the following questions:

10. How can climate change information best be presented to planners of strategy development?
11. How will such information be used or interpreted?
12. What will the probable impacts of climate change be on Alberta's industries, environment, and society?
13. How can negative climate change effects be minimized and positive effects enhanced or exploited?

Interpretation of the results obtained

1. What do the GCM results say for Alberta?

The GCM results examined do not reproduce Alberta's normal climate well. There is a greater discrepancy in the precipitation estimates than in the temperature estimates. The GCM results for the anomalies caused by a doubling of CO_2, however, can be used as first estimates of climate change scenarios due to increased greenhouse warming. The GCM simulations estimate a 3 to 7°C warming for Alberta and a 7 to 30 % increase in precipitation. This would give Alberta a climate similar to present-day Colorado.

2. What are the strengths and weaknesses of GCMs?

GCMs are the best available tools for climate scenario simulation because they include representations of the major physical processes affecting climate. There are, however, many parts that still need improvement, and there are large uncertainties associated with GCM results, particularly for regional applications. GCM results are generally too coarse in resolution for regional assessments (on a scale the size of Alberta), and much of the detail required such as the topography of Alberta, cannot be incorporated. Another weakness of the GCMs involves the time required for running them. Even the fastest of present-day computers require a great deal of CPU time for each simulation run.

3. Can results or simulations from GCMs be modified so as to take into account Alberta's landscape and other regional features?

In order to provide more detailed climate information, GCM results must be modified using one of the approaches to the climate inversion problem. This refers to the problem of relating details of local effects to large-scale climate model results (see the section on model assessment for more discussion). Examples of such approaches include regional climate modelling and statistical estimations. These are needed to modify GCM outputs to take into account Alberta's landscape and other regional features.

4. Are the GCMs useful for planning or strategy development for Alberta?

The value of the GCM results as forecasts for planning or strategy development depends upon the quality of the forecast, the needs of the user, and the knowledge of the user in using the forecast. The quality of the forecast derived from GCMs is poor, however, depending upon the need of the user, there is useful information which can still be extracted. For example, qualitatively, the three GCMs show increases in both temperature and precipitation under a CO_2 doubling situation, although the rates of increase differ. It is important to provide users with some knowledge of GCMs particularly the uncertainties associated with their GCM results.

5. Is the climate of Alberta changing?

From our data analyses, there is certainly a warming trend indicated. The rate of warming is increasing; the 1980s show the maximum warming rate. There is also an overall decrease in the annual mean of the monthly temperature range. In addition, it was found that increases in warming in the winter season were approximately double. It is not possible to determine the causes for such change in recent years. Global effects and local urban warming are two possibilities. No significant change in total annual precipitation was detected.

6. By how much and how quickly has the climate changed?

The temperatures for Alberta in the 1980s (1981-1987) are higher than in the normal period (1951-1980) by approximately 0.2 to 1.4°C depending on location. The change in the mean monthly temperature range varies from 0.8 to over 2.0°C. From a longer term perspective, a long-term rate of warming, which averaged 1.3°C per century and reached a maximum of approximately 4°C per century, was obtained. With warming doubling for the winter season, a maximum increase of approximately 8°C in the average winter temperature over a century can be extrapolated from present results. Considering an estimated CO_2 doubling time by 2030 to 2050 A.D., such warming rates are very similar to the GCM-simulated warming discussed earlier.

7. What are the regional differences in climate within Alberta?

Overall there is a 5°C difference in mean temperature throughout the province and over 300 mm difference in annual precipitation, the minimum being in southeastern Alberta. The mountain areas to the west exert strong local influences on the climate of Alberta. In fact, local differences are reflected in the number of regions into which Alberta is divided by various users of climate information. Our survey indicated a range of 6 to 12 regions for Alberta.

8. Will the frequency of extreme temperature and rainfall events change in Alberta?

The results from our analyses do not allow us to answer this question, and GCM results for extreme events are not widely available. Even without a change in variability, a shift in the mean climate state is sufficient to change the frequency of extreme events if the same definitions are used for these events. Our analyses, however, showed a decrease in temperature range (variability). A more detailed analysis is necessary to quantify changes in the frequency of extreme temperature events. Our analyses showed no definite increases or decreases in precipitation. Even with no change in precipitation, a change in temperature is sufficient to modify the water balance of the earth's surface so that moisture availability is affected.

9. Will the magnitude of these events change?

As discussed above, not only the frequency in extreme events will change, but new extremes of different magnitude will be defined. For example, with a general warming trend and reduced variability, the record highs and lows may both be greater than what we experience today.

10. How can climate change information best be presented to planners for strategy development?

There is a need for different levels of support for the various users of climate information. Some use raw data and others require access to expertise and assistance in the interpretation and dissemination of the data. There is also a high level of interest in the climate information obtainable from models. These include climate models and impact models. Some form of climate centre with the required expertise would be helpful in providing planners with climate information. Ongoing access to climate change information and scientific opinion written in layman's terms is needed.

11. How will such information be used or interpreted?

The survey was designed only to identify the key climate data requirements for strategic planning at the managerial level. More detailed information is needed about how climate information is used at the operational level. An important conclusion reached from the user needs survey regarding the effects of climate change is that there is a lack of confidence in the climate model results. This difficulty is associated with the interpretation of climate information. It can be remedied by providing users with information about GCM characteristics and developments in nontechnical terms.

12. What will the probable impacts of climate change be on Alberta's industries, environment, and society?

In planning the present study it was decided that the first step in developing a strategy for adapting to climate change in Alberta should be to quantify, as much as possible, the climate variability and potential change for Alberta. The next step in the process was seen to be a consideration of biophysical impacts, which would eventually lead to socioeconomic impacts. Thus, the present study was not directed toward impact assessment. From the user needs survey, it was indicated that water-related issues are of major concern to most users. Therefore, future studies on the impacts of climate change, should emphasize water resources issues.

13. How can negative climate change effects be minimized and positive effects enhanced or exploited?

This can only be achieved with an early start on the strategy development process and careful monitoring of climate. Strategy development should include planaction activities, i.e. those activities that can be set in motion now because they make sense whether climate change occur or not and will help address the climate change issue. Activities such as promoting energy efficiency and reducing air pollution would fall into this category.

Conclusions

The principal conclusions that can be drawn from the results of this study are given below:

1. The GCMs are the best available tools for future climate simulations. However, for purposes of regional scale application and assessment, there are large uncertainties associated with the model results. The GCM results do not reproduce Alberta's normal climate well. There are greater discrepancies in the precipitation estimates than in the temperature estimates. GCM simulations of climate under a doubling of atmospheric carbon dioxide suggest an increase of 3 to 7°C in annual temperature and a 7 to 30% increase in precipitation for Alberta. Such increases in annual temperature and precipitation would give Alberta a climate like that of present day Colorado. This situation is expected to be reached by the years 2030 to 2050. It must be noted that an increase in temperature will result in a change in the water balance at the earth's surface (because of increased evapotranspiration) irrespective of any change in precipitation.
2. In the 1980s (1981-1987), the average annual temperature of Alberta was warmer than normal (defined by the period 1951 to 1980) by about 0.2 to 1.4°C, depending upon location. Based on data from 1951 to 1987, the warming rate was estimated to have an average of 1.3°C per century and a maximum of approximately 4°C per century. With warming doubling in the winter season, a maximum increase of approximately 8°C in the average winter temperature over a century can be extrapolated from the present results. No significant change in precipitation was detected. Alberta's climate has significant regional differences. Overall there is a 5°C difference in mean annual temperature over the province and a difference of over 300 mm in annual precipitation, the minimum being in southeastern Alberta. The mountain areas to the west exert strong local influences on the climate of Alberta. In fact, such local differences are reflected in the number of regions into which the province is divided by various users of climate information. Climate data from northern Alberta is sparse.

   Even without a change in climate variability, the shift in the mean climate is sufficient to change the frequency of extreme events. However, in analyzing climate records, the mean monthly range in temperature was the only indicator of climate variability and extreme weather events that was examined. In the 1980s a decrease in the mean monthly temperature range, from 0.8 to more than 2.0°C was detected, suggesting a decrease in the occurrence of temperature extremes.
3. The important conclusions from the user needs survey regarding the effects of climate change is that there is a lack of confidence in the climate model results. This lack of confidence is partly due to difficulties associated with the interpretation of climate information. Weather monitoring is carried out by a number of agencies but the data are not archived collectively and are therefore not easily accessible to others. Trained support staff are required to provide professional and consistent analysis and interpretation of climate data. Managers are willing to use climate variability and climate change information in the planning process if the information available is in an understandable form and associated uncertainties are identified. The survey also pointed out that water-related issues are major concerns of most users.

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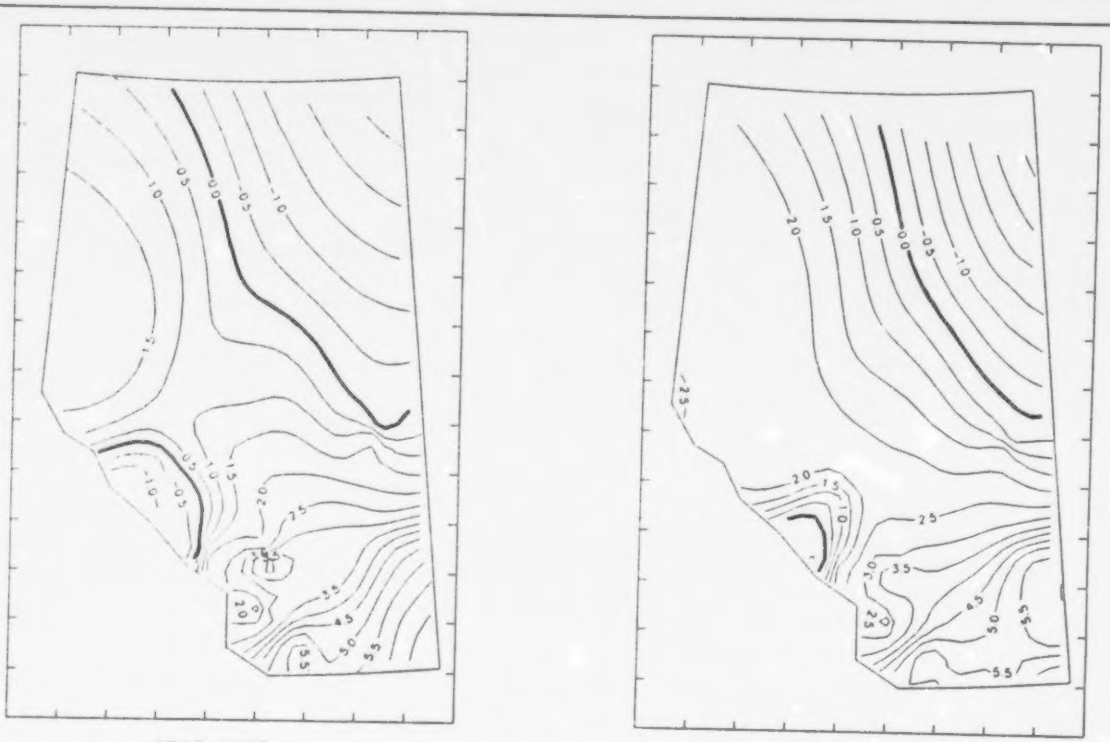
Appendix A. Trend estimates from individual stations.

Table of long-term trends in annual mean temperature, annual average of monthly temperature range and annual total precipitation at observation stations.

Station	Temperature °C (100 yr)$^{-1}$	Range °C (100 yr)$^{-1}$	Precipitation mm yr^{-1} (100 yr)$^{-1}$
Banff	1.34	-2.25	-60.3
Beaverlodge	-0.62	-2.75	49.3
Beaver Mines	2.58	-6.86	-123.0
Caldwell	1.62	0.73	-83.6
Calgary	0.44	-2.21	-18.0
Calmar	1.38	-8.55	68.6
Campsie	0.20	-6.77	19.9
Camrose	4.35	-8.69	295.4
Cardston	0.53	-1.36	111.6
Carway	1.41	4.53	85.7
Coronation	1.30	4.25	114.5
Edmonton	3.90	-9.78	45.7
Elk Point	2.43	-3.53	136.8
Entrance	-0.12	-7.01	-97.2
Fairview	2.78	-8.61	62.4
Fort McMurray	5.18	-7.72	-11.0
Fort MacLeod	0.52	-1.65	86.5
Gleichen	0.61	0.42	27.3
Grande Prairie	3.54	-3.88	-212.7
High River	-0.29	-5.82	-124.7
Jasper	0.80	-6.29	-46.5
Kananaskis	1.30	-1.26	-52.5
Lacombe	0.10	-6.04	-24.9
Lake Louise	-0.47	-3.79	-127.0
Lethbridge A	0.64	-0.13	-172.7
Lethbridge CDA	1.06	-2.31	-20.1
Manyberries	-0.01	-3.49	195.5
Medicine Hat	-0.46	-1.74	-8.4
Olds	0.21	-3.70	36.3
Pekisko	-0.56	-2.62	159.5
Ranfurly	0.91	-7.83	-86.1
Red Deer	1.16	-1.02	105.1
Rocky Mountain House	1.67	-3.79	10.3
Suffield	3.69	-3.08	-57.8
Taber	2.66	-1.93	-114.9

Appendix B1. Spatial distribution of temperature mean and trend for partition II.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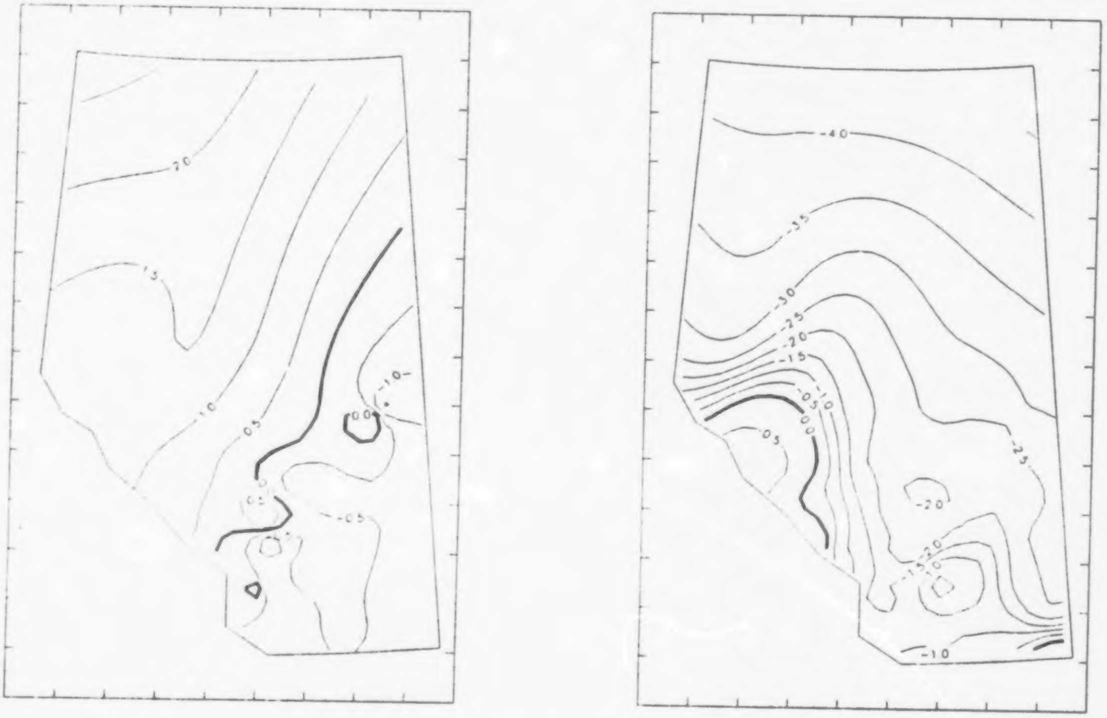
1918-1927

1928-1977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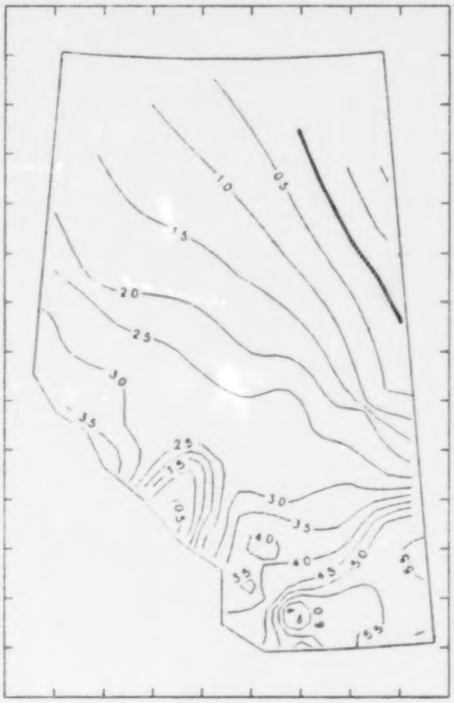
Appendix B1. (continued)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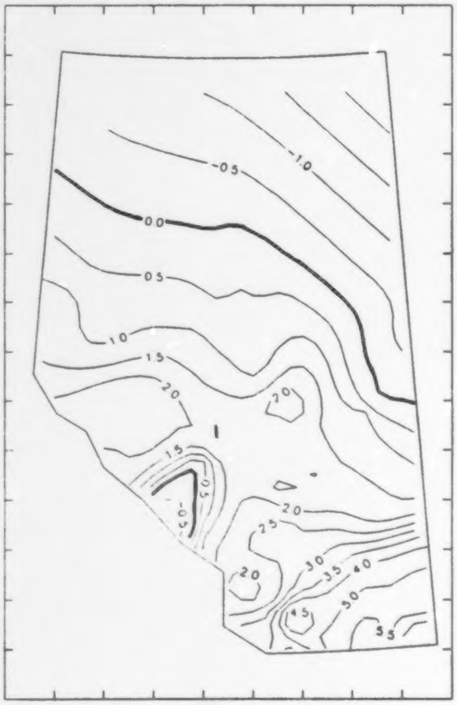
1938-1947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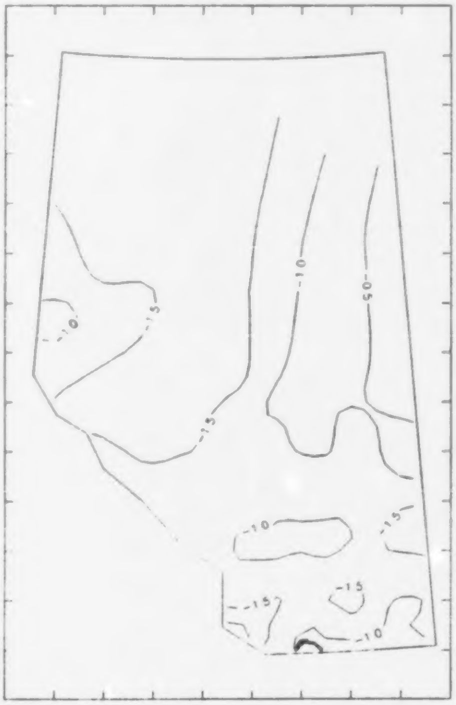
1948-1957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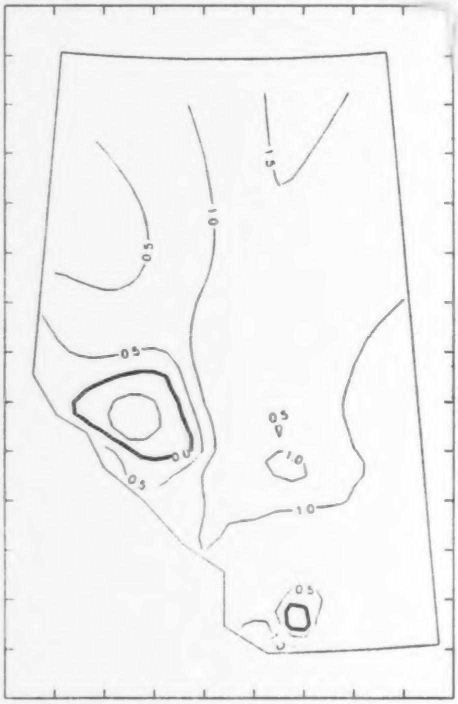
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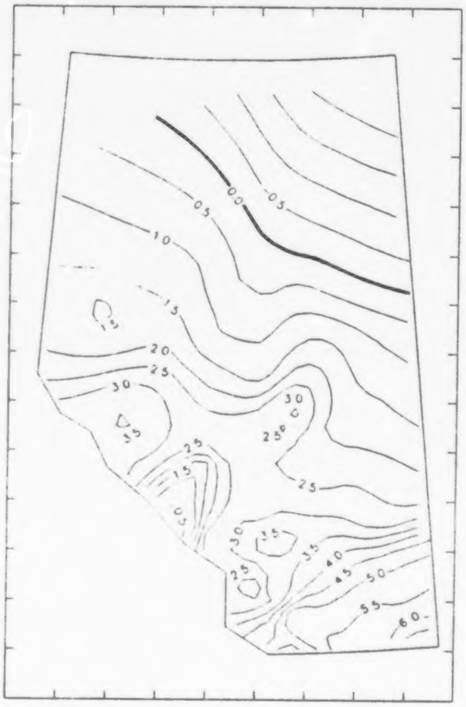
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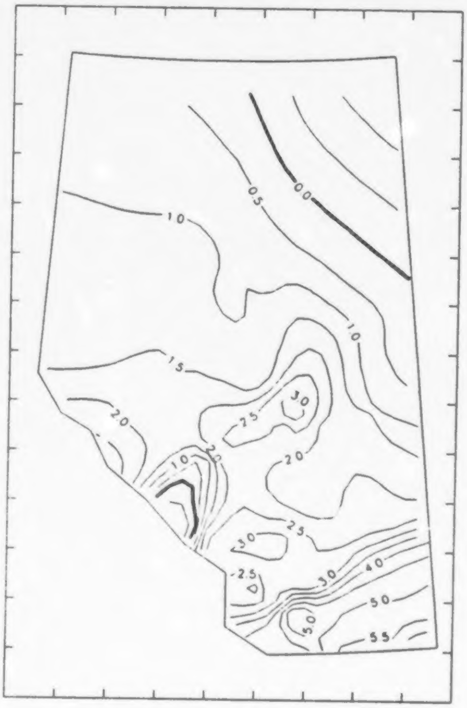
1958-1967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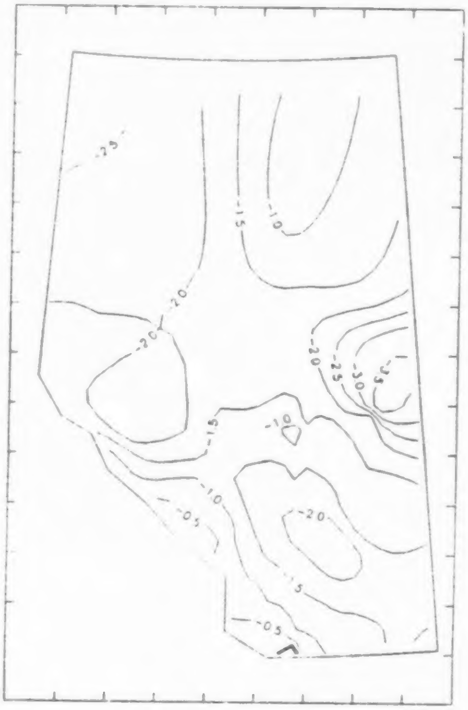
1968-1977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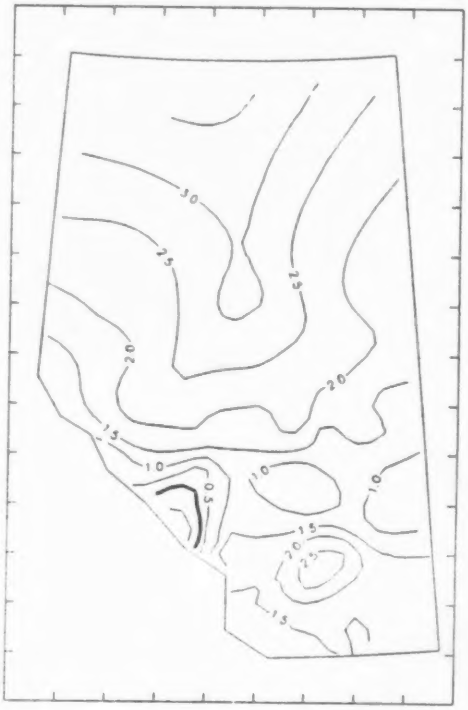
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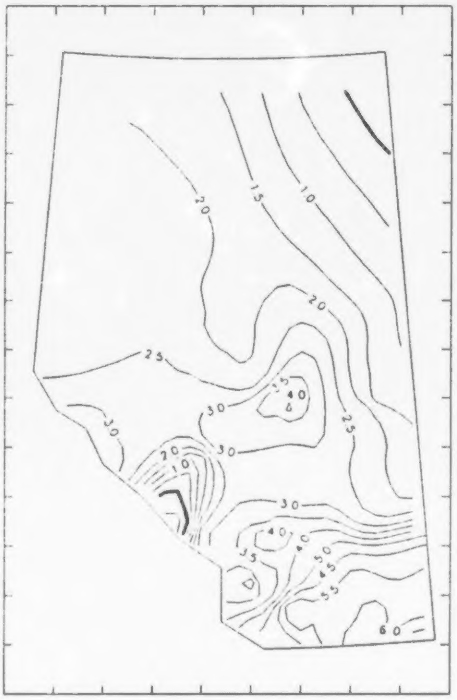
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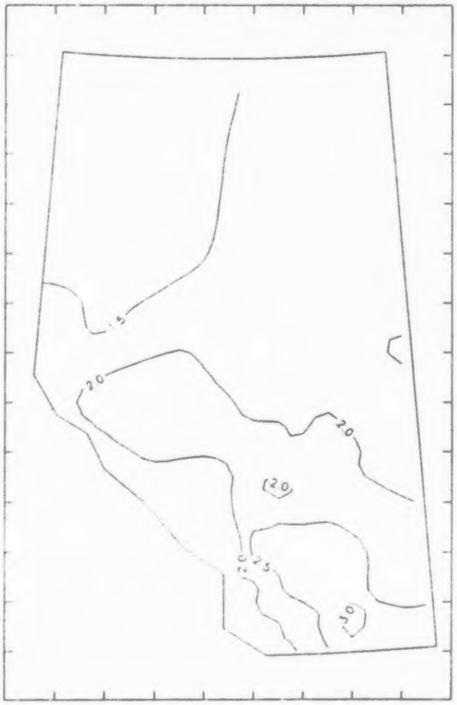
1978-1987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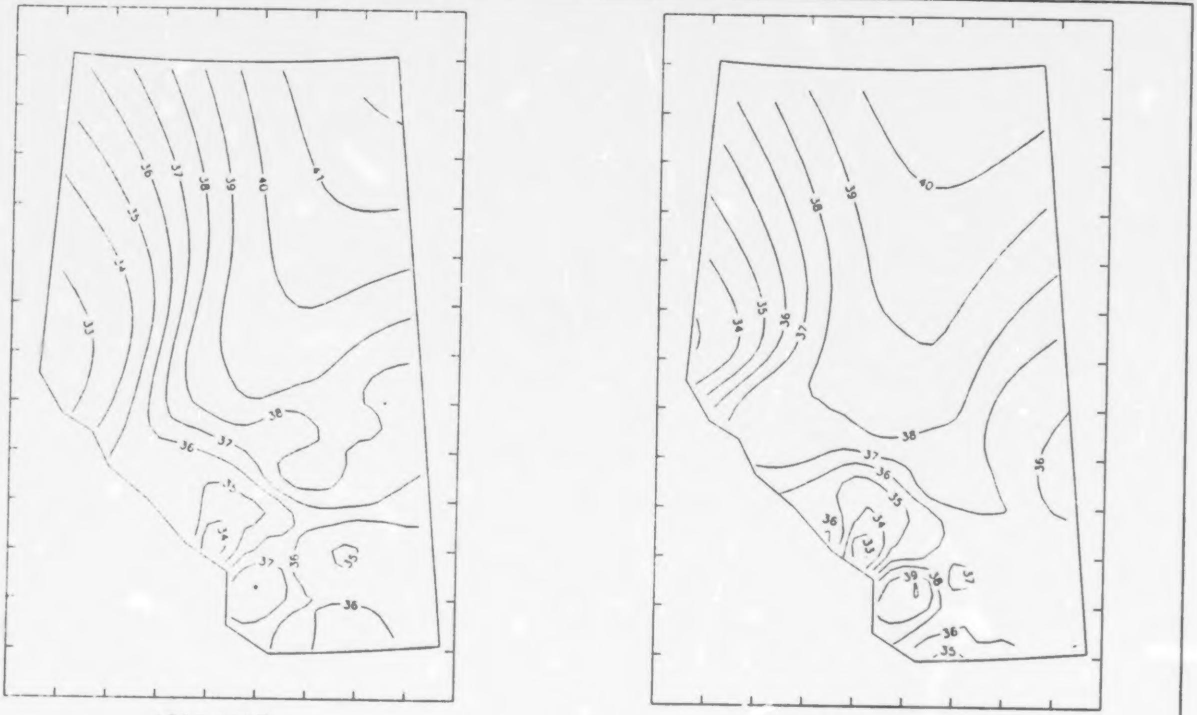
Appendix B2. Spatial distribution of annual mean of monthly temperature range and its trend for partition II.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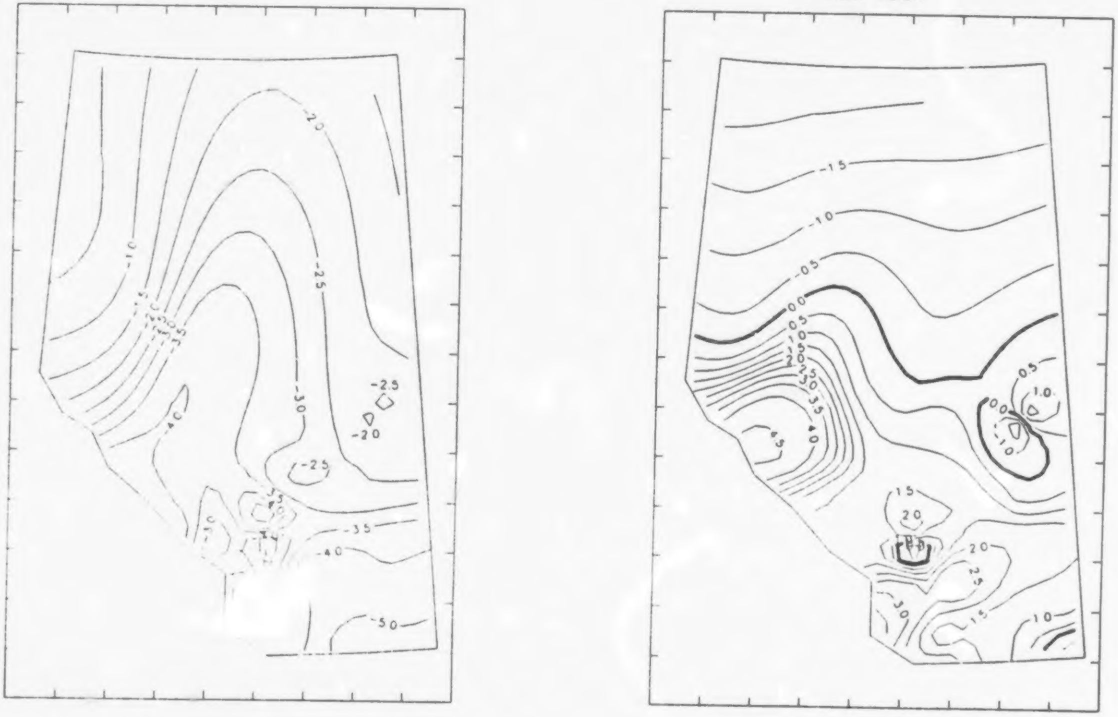
1918-1927

1928-1937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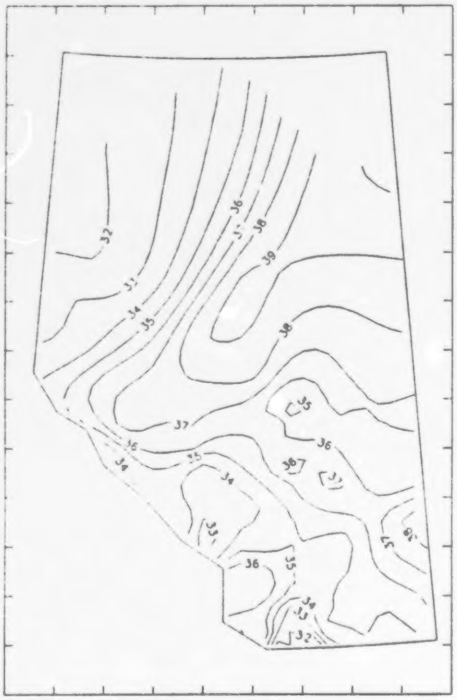
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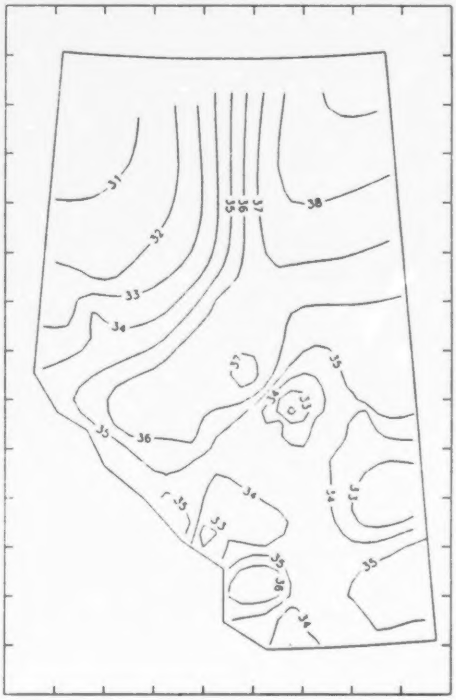
1938-1947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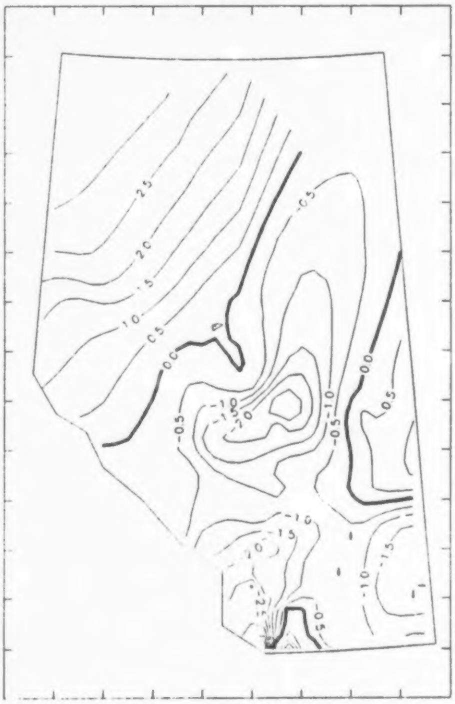
1948-1957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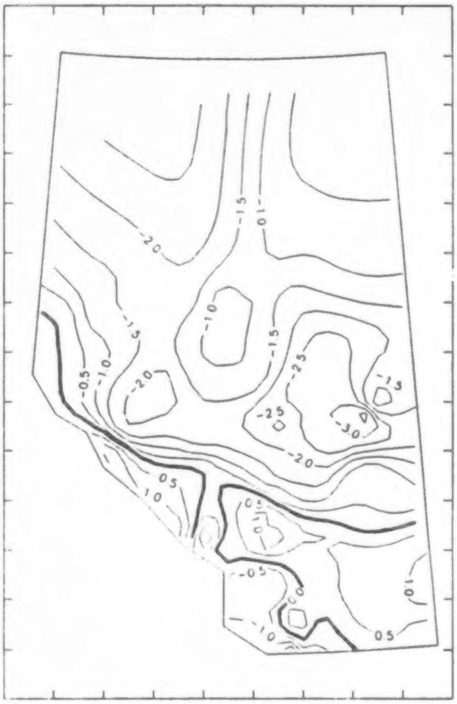
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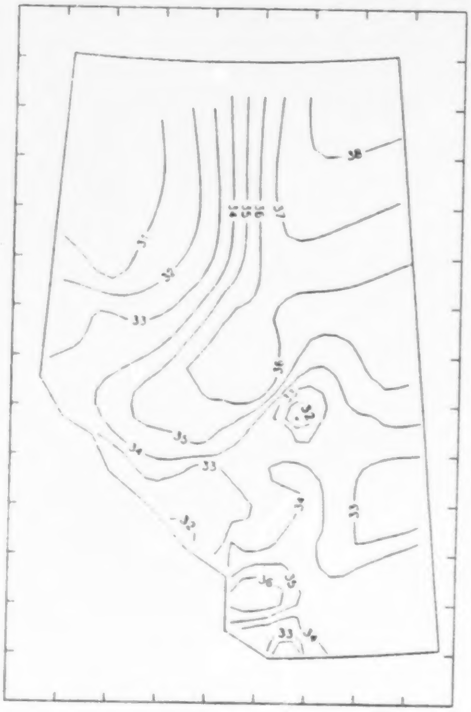
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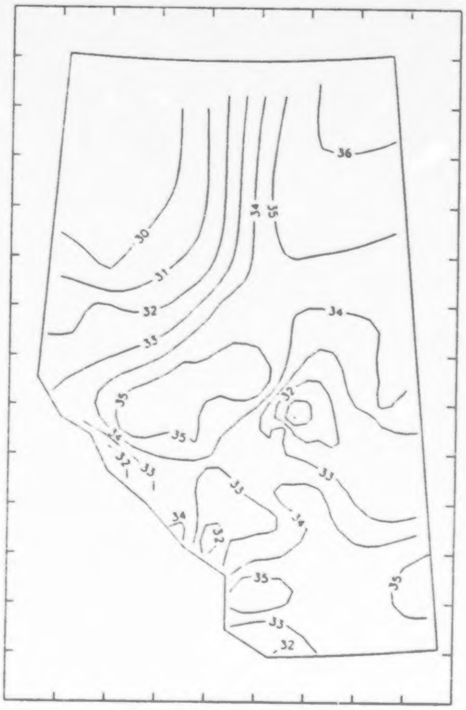
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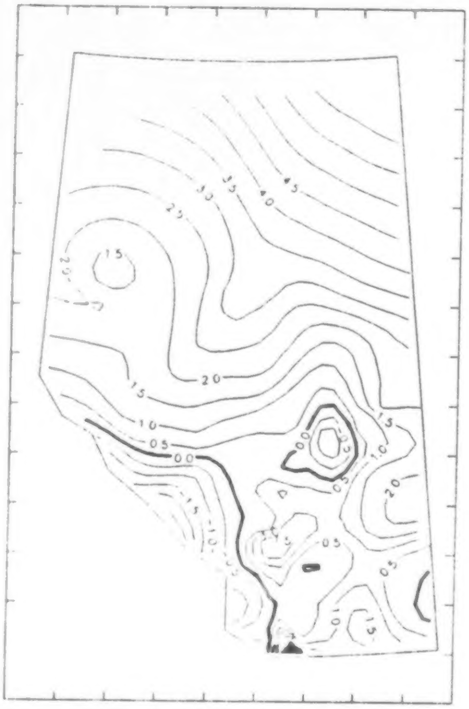
1968-1977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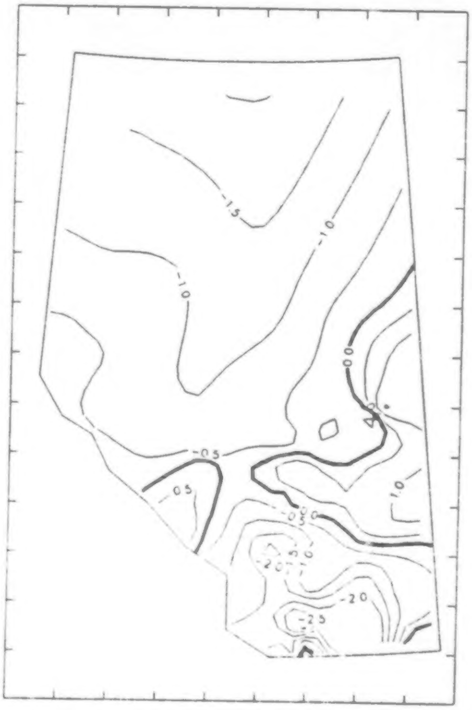
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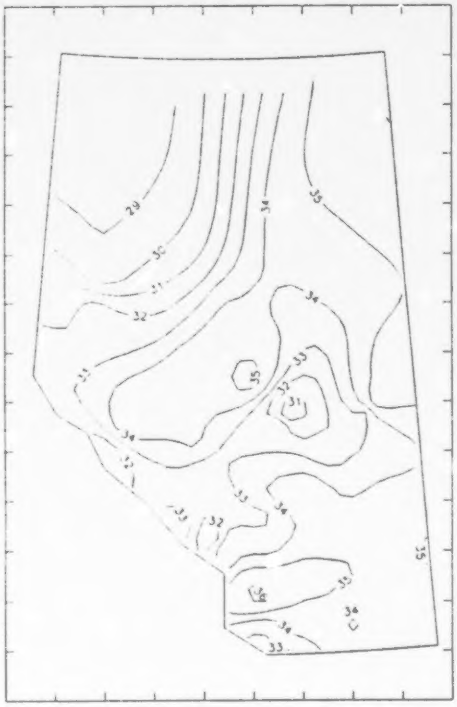
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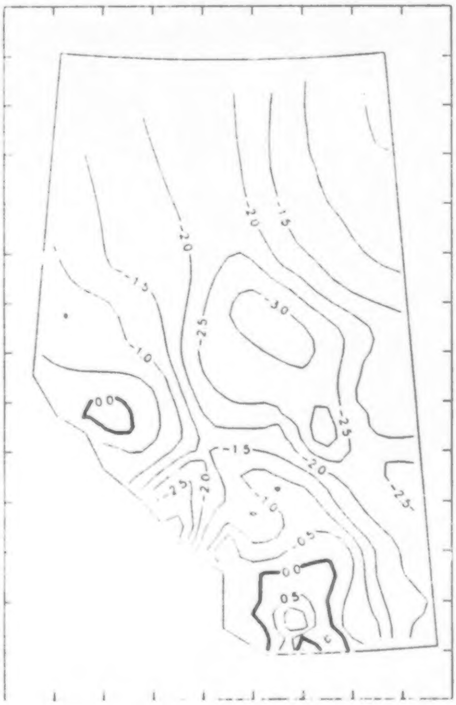
1978-1987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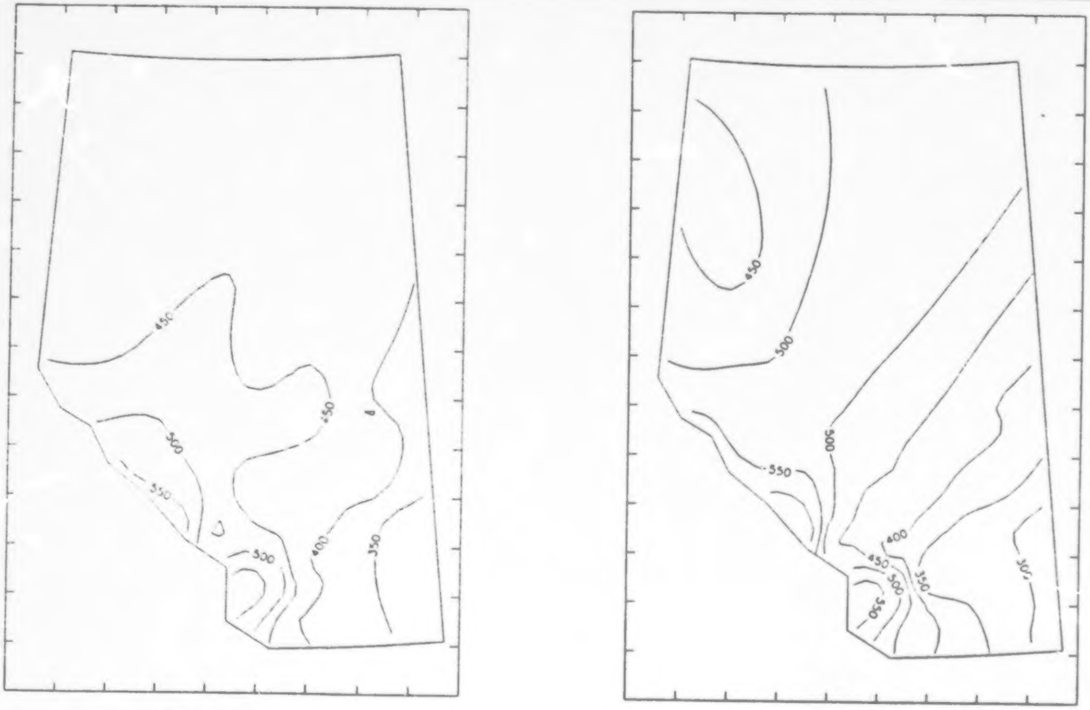
Appendix B3. Spatial distribution of annual total precipitation and its trend for partition II.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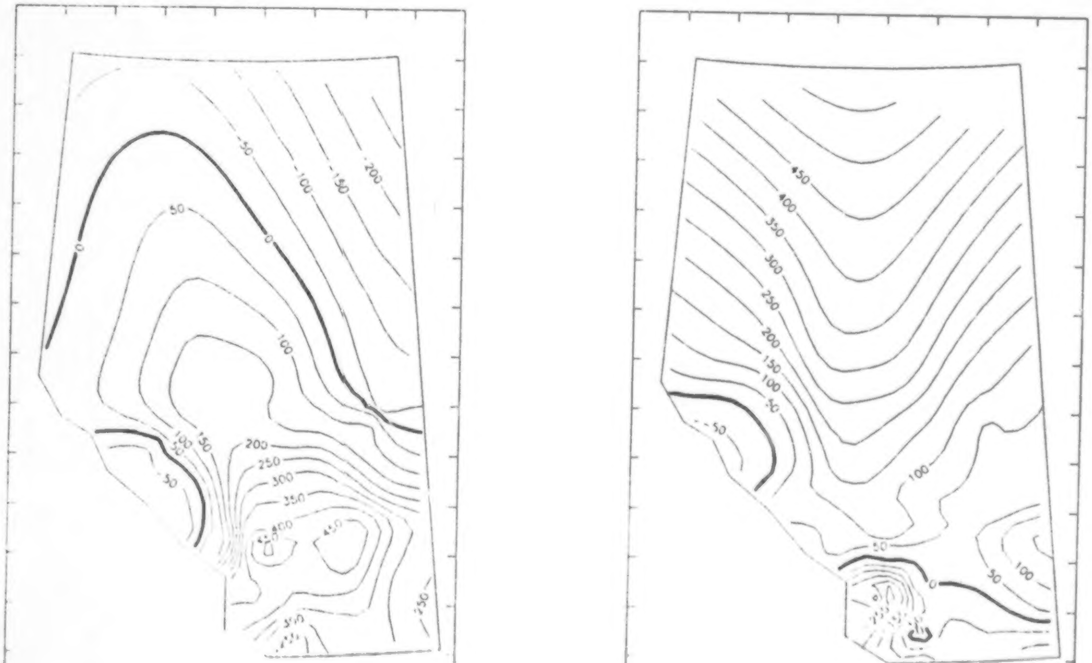
1918-1927

1928-1937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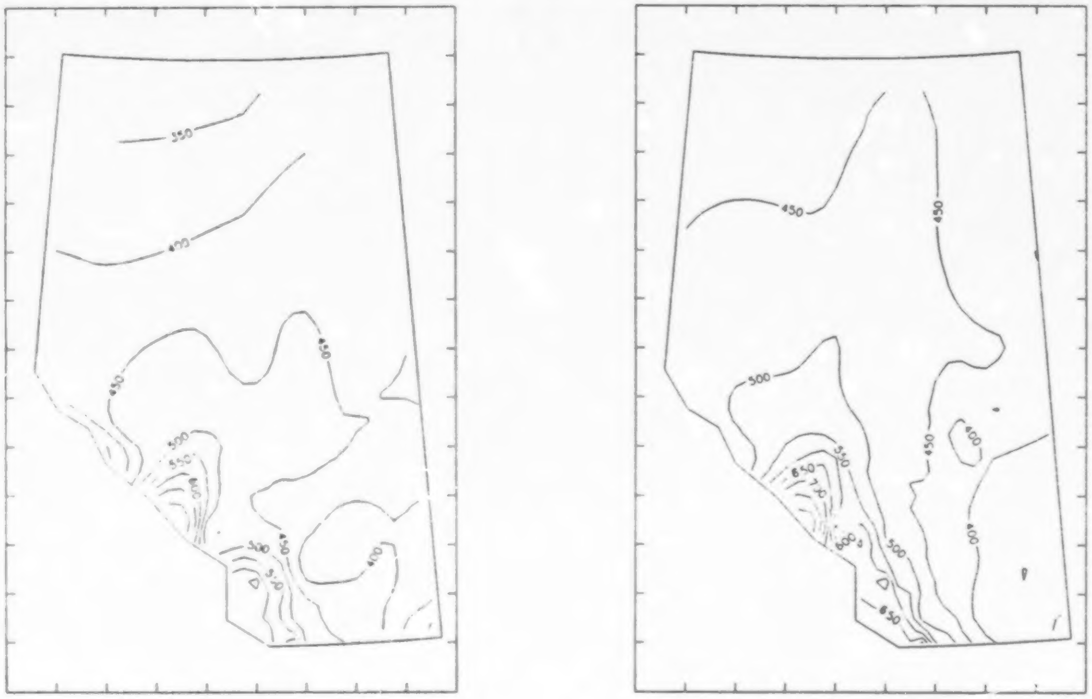
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1938-1947

1948-1957

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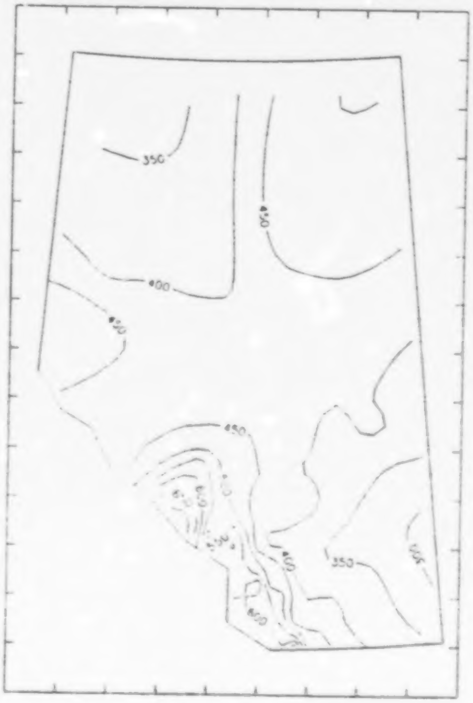
Appendix B3. (continued)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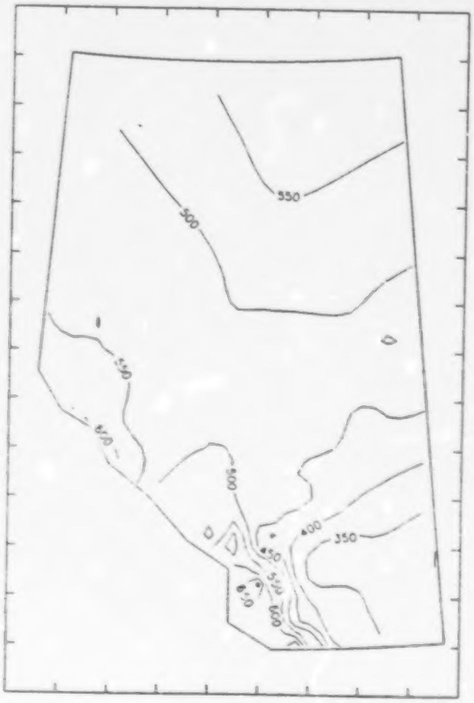
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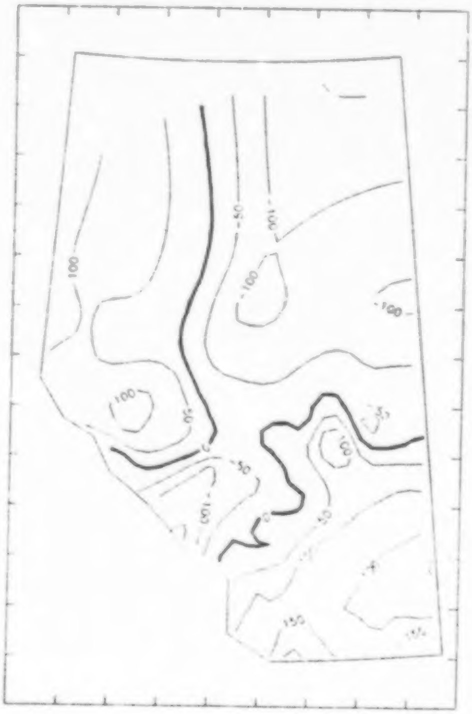
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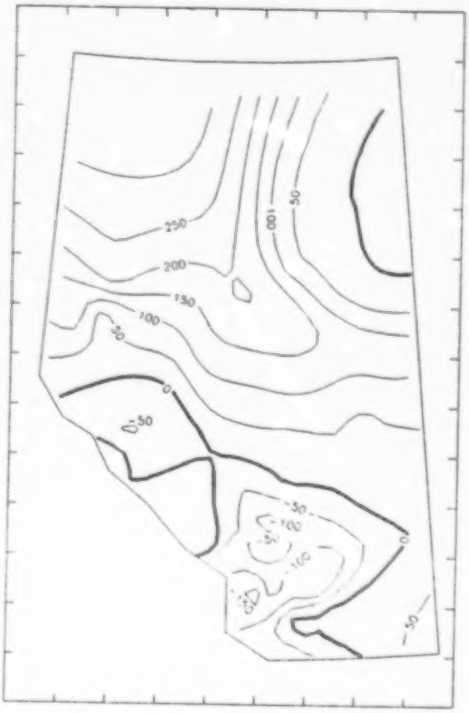
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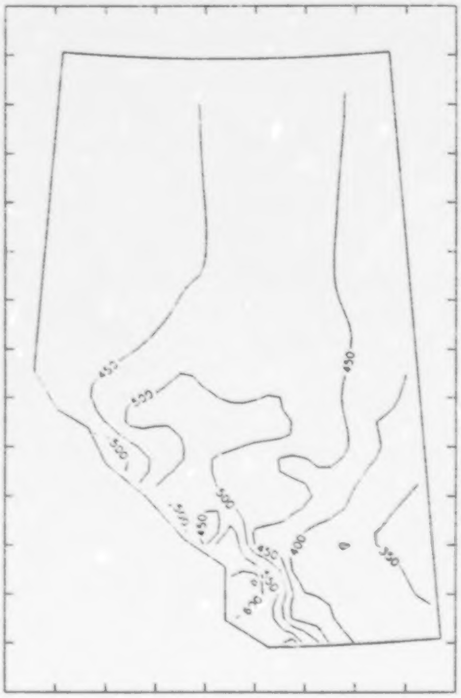
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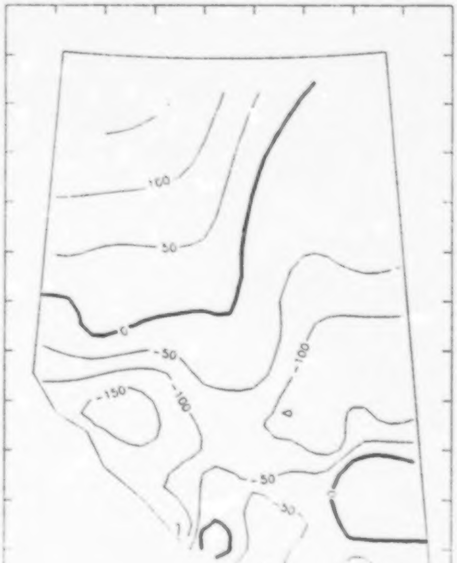
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Appendix C. Climate user needs survey questionnaire.

Towards a strategy for adapting to climate change in Alberta

Survey questions

1. What programs are you responsible for? Are there any new programs planned for the next five years?
2. What is the impact of weather or climate on those projects?
3. Do you use climate-based information for your current operational or planning requirements? If so what space and time scale is required?
4. Do available climate-based data meet your current management and planning needs?
5. Do you require additional climate-based data for planning? If so, what would be the preferred space and time scale requirements?
6. What is the most important climate-based data? Do you have problems getting that data?
7. How would you like climate-based information to be presented? Would you prefer that information on climate change scenarios be expressed in probability or "risk analysis" terms?
8. Is short term climate variability important to your current planning needs? Do you expect short term climate variability to become important for your future planning needs?
9. Is medium or longer term climate change important to your current planning needs? Do you expect medium or longer term climate change to become important for your future planning needs?
10. Which is of greater concern, climate variability or climate change?
11. How important is the rate of onset of climate change to your planning process? How important is advanced warning of climate change or variability?
12. Are you using any application/impact models in your work (i.e. crop yield forecast models, water availability forecast models, flood forecasting, assessing regional potential for sustaining a new crop)?
13. What would be your principal geographic region of interest regarding planning for climate change?
14. Would climate impacts on geographic areas OUTSIDE of Alberta be of importance for planning purposes?

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